AFML-TR-72-40

AN EXPERIMENTAL INVESTIGATION OF THE STRESS LEVELS AT WHICH SIGNIFICANT DAMAGE OCCURS IN GRAPHITE FIBER PLASTIC COMPOSITES

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Air Force Materials Laboratory

Air Force Systems Command

Wright-Patterson Air Force Base, Ohio 45433

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RESEARCH AND TECHNOLOGY WORK UNIT SUMMARY

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01. AGCY ACCESSION	02. DATE OF SUMM	04. KIND OF SUMM REPORT	REPORTS CONTROL SYMBOL
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PRIMARY NUMBER/CODE

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23. (U) This work will establish increased confidence in the application of graphite fiber reinforced components to structural uses in AF flight vehicles and missiles and provide a baseline for development in detection of damage in service. It is the purpose of this investigation to attempt by experimental means a rigorous definition of the stress level within a composite specimen at which physical damage and/or degradation of mechanical properties are initiated such that the material resistance to subsequent loadings is seriously impaired. The work will be important in the establishment of realistic limit stresses for plastic composite structures.

24. (U) Unidirectional and multidirectional composites will be initially stressed to a predetermined value and reloaded under various states of stress, including biaxial stresses and cyclic loading. By varying the initial stress condition and inspecting for subsequent physical damage and determination of property degradation, a limit stress or proportional limit stress will be defined.

25. (U) None

New Work See DF671770

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FOREWORD

The research and development reported herein was conducted under the Air Force Contract F33615-70-C-1330 by Southwest Research Institute. The work was initiated under Project 7340, "Nonmetallic and Composite Materials," Task 734003, "Structural Plastics and Composites". The Air Force Project Engineer directing the program was Dr. J. M. Whitney, of the Plastics and Composites Branch, Nonmetallic Materials Division, Air Force Materials Laboratory at Wright-Patterson Air Force Base, Ohio. Mr. Glenn C. Grimes was Project Leader at Southwest Research Institute, working under the direction of Mr. L. U. Rastrelli, Assistant Director, and Dr. R. C. DeHart, Director, Department of Structural Research. Dr. P. H. Francis was Assistant Project Leader in charge of the biaxial testing phases of the program with facilities and personnel of the Department of Mechanical Sciences, Dr. H. Norman Abramson, Director.

The work covered in this report was directed and performed by the following SwRI engineers and scientists:

G. C. Grimes, Project Leader and Principal Investigator—Material Selection, Test, and Allowables Criteria

P. H. Francis, Assistant Project Leader and Principal Investigator—Biaxial Testing of Tubes and Associated Test Plan

G. E. Commerford, Principal Investigator—Processing, Tooling, Quality Control, and Associated Testing

G. K. Wolfe, Principal Investigator—Experimental Program, Micro/Macromechanics, and Tooling Design

In addition, the assistance of Dr. L. F. Greimann on laminate analysis is recognized and the able performance of Mr. W. H. Keith and Mr. A. R. Reichert in laboratory processing and testing is appreciated. Mrs. Jane Baker's work in typing the Draft Final Report is recognized.

The report covers work conducted February 1970 through December 1971.

This report has been reviewed and is approved.

T J Reinhart

T. J. Reinhart
Acting Chief, Plastics and Composites Branch
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ABSTRACT

Significant damage stress levels in HTS/ERLA-2256 graphite epoxy composites were investigated in this research program. In order to do this it was necessary to establish high quality fabrication and inspection techniques for processing flat laminates and tubes and to experimentally characterize the mechanical and physical properties of the composite (lamina and laminate). Two significant damage stress levels were observed in $[0/90]_c$ laminates and related to the material's mechanical behavior. Empirically modified micro/macro-mechanics techniques and maximum strain theory were used to predict these stress levels as well as other composite properties with reasonable accuracy. These predicted values are used in normalizing the experimental data to one fiber and void volume for direct comparison and statistical analysis. Material design allowables and confidence limits on the composite properties were established and possible application criteria proposed.

Significant milestones accomplished during the program include: (1) the development of new processing techniques for the new prepreg version (Fiberite HY-E-1317B) of the HTS/ERLA-2256 graphite/epoxy material system, (2) development of quality seamless tube fabrication tooling and processing techniques, (3) establishment of improved instrumentation and automated data recording procedures along with semiautomated data reduction methods, (4) development of axial and biaxial tube testing techniques, and (5) the discovery of two significant micromechanical damage stress levels in the $[0/90]_c$ orientations which cause a change in subsequent loading behavior.

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SECTION I

INTRODUCTION

The purpose of this program was to conduct an exploratory experimental investigation to determine significant damage stress levels (if any) in graphite/epoxy composites. Courtauld's HTS treated meter length tow impregnated with UCC ERLA 2256 modified epoxy resin was used as the raw material. It was procured from Fiberite Corp. as a "B" staged prepreg with the commercial designation HY-E-1317B and laminated and cured at SwRI. Test specimens were fabricated and instrumented from panels and tubes with $[0]_c$ and $[90]_c$ lamination sequences relative to the principal axis* and studied in tension, compression, and planar shear for static lamina characterization purposes. A similar experimental evaluation was performed on $[0/90]_c$ and $[90/0]_c$ lamination sequence specimens which were characterized statically in the same tension, compression, and planar shear modes but in addition were studied (in a limited manner) under static biaxial stresses. These data provided the foundation for the "significant damage stress level" study which followed.

Two basic techniques were used to ascertain significant damage from a physical and mechanical viewpoint. First longitudinal and transverse (to the principal axis) strain gages were used on most of the specimens to thoroughly characterize them as well as to pick up any anomalies which might occur in the stress-strain behavior. Second, the microscopic examination of longitudinal and transverse cross-section cuts on specimens which had been stressed to predetermined levels, but not failed, were utilized to establish physical micromechanical damage. Relating this damage to changes in subsequent loading mechanical behavior proved more difficult.

Because of the high degree of anisotropy of the $[0/90]_c$ and $[90/0]_c$ orientations, tensile loading damage in the 90° plies had little or no effect on subsequent static tension loading properties except to change the Poisson's ratio. Subsequent loading in a different direction (compression) did affect the mechanical behavior as did tensile fatigue ($R = 0.05$) loadings in which the maximum alternating stress was above the damage level stress. Compression load damage to the 0° plies was discovered with some subsequent compression loading effects evident. Subsequent loading in tension after initial loading in compression to or above the damage stress level had no effect. The significance and consequence of these effects were then investigated.

Effects of such damage on micro-macro-mechanics and failure theories were studied as well as discussing the importance of such effects on design allowables. Basically micro/macro-mechanics normalization of the experimental and analytical data was accomplished in order to study it more realistically. Some statistical analysis was performed but insufficient data was available for a rigorous investigation of this kind. Design allowables were determined in a somewhat unorthodox fashion because of the limited data, but utilizing the damage found as a basis for them. Partial static experimental failure surfaces were developed for $[0]_c$ laminas and $[0/90]_c$ laminates. Maximum strain theory as a strength predictive method appears to work well for tension and compression axial and biaxial loadings but becomes very conservative for planar shear loading either by itself or in combination with other loadings. However, the biaxial tube data is too limited to confirm the combined load behavior observed beyond a reasonable doubt.

In the body of this report, details of the investigation are covered in more or less chronological fashion. Section II presents the detail Process Development and Fabrication effort including the design and fabrication of the SwRI seamless composite tubes. Materials Experimental Characterizations are covered in Section III including the micro- and macro-mechanics normalization techniques used on both flat specimen and tube experimental data. Section IV on Significant Damage Stress Level Evaluation satisfied the basic objectives of the program by identifying and characterizing two types of significant damage. Material Design Allowables Criteria Implications of the significant damage discovered are discussed in Section V, whereas, Section VI presents the Conclusions and Recommendations based on the program results, including the significance of the study on composite applications. Following the

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*The first of the two principal material axes.

List of References, four Appendices (I through IV) are included covering detailed specification and literature information used in the program, selected experimental data, and the design drawings used in the program's performance.

The authors judge the program as successful, having achieved the major objectives established in the beginning. However, the program results suggest many more questions than answers.

The program consisted of five tasks as follows:

Task I —Design, Materials, Processes, Fabrication, and Quality Control

Task II —Control Specimen Characterization and Experimental Evaluation

Task III —Initial/Subsequent Loading Damage Level and Residual Strength (Modulus) Investigation

Task IV —Experimental Data Reduction, Analysis, and Correlation

Task V —Design Allowables Criteria Implications

SECTION II

PROCESS DEVELOPMENT AND FABRICATION

1. GENERAL

This section will provide a detailed description of the process development, fabrication and quality control methods utilized in the preparation of flat panels and tubes for use as test specimens in Tasks I, II, and III of the experimental program. Flat panels of laminated composite construction are discussed in Section 2, and the composite tubes are covered in Section 3.

Task I consisted of material selection, test specimen design, flat panel tube process development and manufacture, specimen fabrication, and inspection and quality control. Task II covered control specimen characterization and experimental evaluation. Task III included the initial/subsequent loading damage level and residual strength (modulus) investigation.

2. FLAT PANELS

a. Initial Fabrication

The HTS graphite fiber/2256 epoxy resin prepreg was ordered from Fiberite Corp. in sheets 12 inches by 45 inches to meet the requirements of Specification SwRI-S3-202.* Initial fabrication of flat panels from this material was in accordance with Specification SwRI-S3-302.* Panels C-1 through 18 were prepared as shown in Table I.

TABLE I

FABRICATION OF FLAT PANELS

Panel No.	Part No. 03-2776-01	Size* (inches)	Fiber† Orientation	No. of Plies	Thickness (inch)	Thickness per Ply (in.)
C-1	X	9 x 6	$[0]_{10T}$	10	0.1051	0.0105
C-2	4-3	15 x 3	$[0]_{4T}$	4	0.045	0.0112
C-3	4-5	3 x 15	$[90]_{4T}$	4	0.045	0.0112
C-4	4-7	15 x 3	$[0/90]_S$	4	0.044	0.0110
C-5	4-9	3 x 15	$[90/0]_S$	4	0.045	0.0112
C-6	4-11	15 x 3	$[0]_{12T}$	12	0.121	0.0101
C-7	4-13	3 x 15	$[90]_{12T}$	12	0.125	0.0104
C-8	4-15	15 x 3	$[0/90]_{3S}$	12	0.125	0.0104
C-9	4-17	3 x 15	$[90/0]_{3S}$	12	0.125	0.0104
C-10	5-3	10.5 x 8	$[0]_{3T}$	3	0.033	0.0110
C-11	5-7	8 x 10.5	$[90]_{4T}$	4	0.040	0.0100
C-12	5-5	10.5 x 8	$[0]_{12T}$	12	0.1325	0.0110
C-13	5-9	8 x 10.5	$[90]_{12T}$	12	0.1315	0.0109
C-14	5-7	8 x 10.5	$[90]_{4T}$	4	0.043	0.0108
C-15	5-11	10.5 x 15	$[90/0]_S$	4	0.041	0.0102
C-16	5-13	10.5 x 12	$[90/0_2/90]_{3T}$	12	0.117	0.0098
C-17	5-13	10.5 x 12	$[90/0_2/90]_{3T}$	12	0.116	0.0097
C-18	5-11	10.5 x 15	$[90/0]_S$	4	0.040	0.0100

*Surface ply fibers are oriented in the direction of the first dimension listed.

†Fiber orientation is with respect to the long axis of the panel.

The part number in the table refers to the drawing numbers as presented in Appendix I. Panel C-1 is a material acceptance test panel and was given the designation of Part No. X. The 9-inch by 6-inch by 10-ply, $[0]_{10T}$ layup permitted this panel to be prepared from one sheet of the 12-inch by 45-inch prepreg material.

*See Appendix I.

At the time that Panel C-1 was fabricated, the ultrasonic inspection facility was inoperative. In order not to delay the test program, it was decided to proceed with the acceptance tests without the ultrasonic inspection. The panel was cut and specimens submitted for determination of transverse and longitudinal flexure strength and modulus and short beam horizontal shear strength. Specimens were also submitted for determination of specific gravity and fiber content. All of the flexure specimens were tested at a span of 2 inches. Results of these tests are given in Table II along with the values specified in SwRI-S3-202.* Although the longitudinal flexure strength is lower than

TABLE II

SwRI ACCEPTANCE TEST
Panel No. C-1

June 25, 1970
by
R. L. Tuck

Fiberite Hy-E-1317-B Graphite/Epoxy Prepreg Lot OB-6-1, Sheet Nos. 1-31:
Laminate Fiber Orientation 0°
Laminate Thickness = 0.1051 in.
Composite Density = 1.475 gm/cc
Fiber Content: 57.64% by wt, 48.32% by volume
Void Volume = 0.88%

Physical Property	Test Temp. (°F)	Spec. No.	Results	SwRI S3-202
Ultimate Flexural Strength-Longitudinal (psi)	RT	C-1-1	165,500	
	RT	C-1-2	168,000	
	RT	C-1-3	168,000	
		Average	167,200	200,000
Flexural Modulus-Longitudinal (psi)	RT	C-1-1	19.35×10^6	
	RT	C-1-2	21.50×10^6	
	RT	C-1-3	21.40×10^6	
		Average	20.70×10^6	
Flexural Strength-Transverse (psi)	RT	C-1-4	11,100	
	RT	C-1-5	11,200	
	RT	C-1-6	10,800	
		Average	11,030	8,000
Flexural Modulus-Transverse (psi)	RT	C-1-4	1.16×10^6	
	RT	C-1-5	1.14×10^6	
	RT	C-1-6	1.18×10^6	
		Average	1.16×10^6	
Horizontal Shear Strength-Longitudinal (psi)	RT	C-1-7	9,780	
	RT	C-1-8	8,700	
	RT	C-1-9	8,800	
	RT	C-1-10	9,250	
		Average	9,132	14,000

NOTE: Span for both longitudinal and transverse flexure tests was 2 in. with quarter point loading. Horizontal shear test span was 0.4 inch. Loading rate was 0.050 in./min for all tests.

specified, it was comparable with values reported in other research efforts at that time. This was considered acceptable for laminates of this fiber content and ply thickness, and fabrication of panels for Task I and II tests specimens was started. As shown in Table I all of these had a ply thickness of 0.010 to 0.011 inch.

It was decided to repeat the flexure tests on Panel C-1 with specimens cut to provide a span-to-thickness ratio of 32 for the longitudinal specimens and 25 for the transverse specimens. These dimensions for flexure specimens have been reported to provide optimum results. Since the ultrasonic inspection equipment was then available, the remnant of Panel C-1 was inspected and a chart of this inspection is shown in Figure 1. A slightly flawed area is

*See Appendix I.

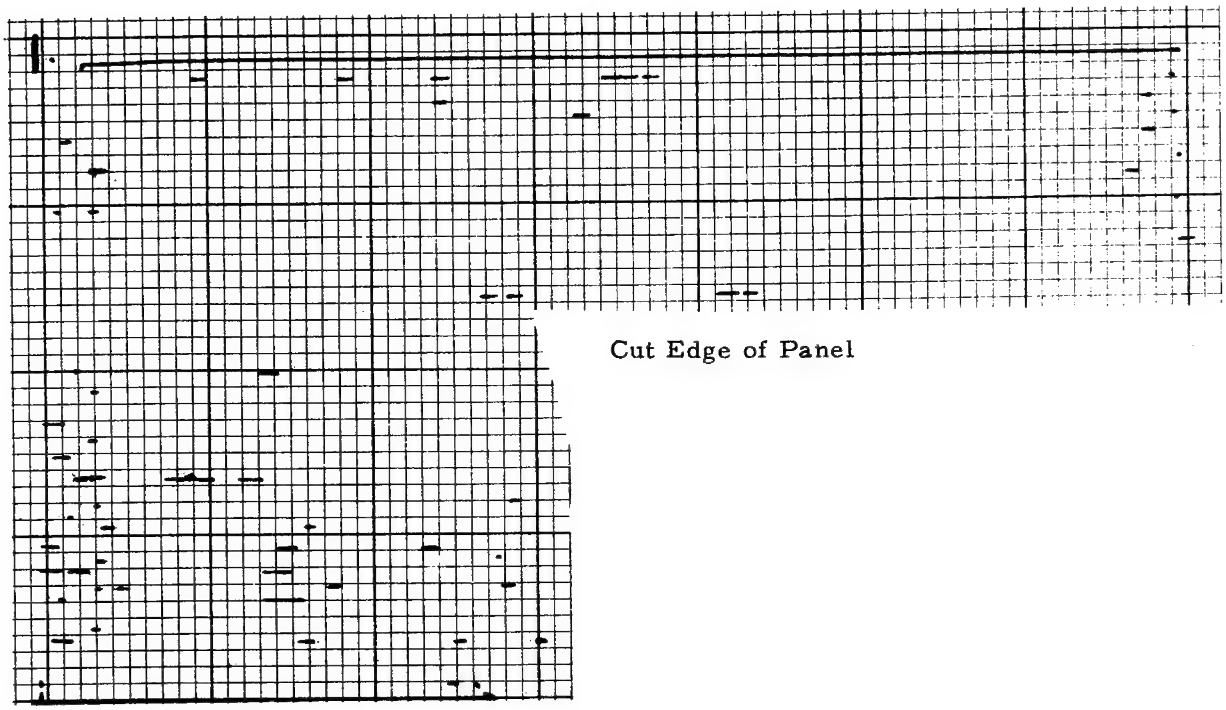

FIGURE 1. ULTRASONIC INSPECTION CHART OF PANEL C-1 (PARTIAL)

indicated in the lower left portion of the panel. The panel was placed in the water bath for ultrasonic inspection without applying tape or other waterproof coating to the cut edge of the panel and then left in the bath overnight. The results of the flexure tests run on specimens subsequently cut from this panel may have been affected by water intrusion into the panel. Results of the repeat tests with increased span/thickness ratio are shown in Table III. Both the longitudinal and transverse flexure results are lower than the original tests and appear to have a greater variance. Although the horizontal shear results are slightly higher than the original test, this does not appear to be significant.

It had been noted that most of the panels fabricated through No. C-18 had a resin starved appearance on the bottom surface. Also, the ply thickness of 0.010 inch or more* and fiber volume of less than 50% indicated that insufficient resin was being bled from the layup. These panels had one bleeder ply (120 glass cloth) for each 4 to 6 plies of prepreg. It was therefore decided to conduct a brief process development program to determine if resin bleedout could be increased to yield a panel with improved properties.

b. Process Development

The process development program had as its principal objective the improvement of the composite properties (flexural strength and modulus and horizontal shear strength) and reduction of thickness per ply with an increase in fiber volume percent to the range of 55 to 60%. Five panels were fabricated with changes in the number and arrangement of the bleeder plies and cure pressure. These panels were identical to the material acceptance test panels. Both process development and acceptance test panels are listed in Table IV with pertinent information on the lay-up and cure, testing, and physical and mechanical properties.

For Panel C-19, the only change in lay-up and cure from Panel C-1 was the use of two additional bleeder plies. Two more bleeder plies were added for panel C-20 and the total load on the cure press was increased from 12 tons to 15 tons. Neither of these panels shows significant improvement over Panel C-1. The bottom surface of

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*Now judged to be too thick for this material.

TABLE III

SwRI ACCEPTANCE TEST
Panel No. C-1

July 7, 1970
by
G. E. Commerford

Fiberite Hy-E-1317-B Graphite/Epoxy Prepreg Lot OB-6-1, Sheet Nos. 1-31:
Laminate Fiber Orientation 0°
Load Orientation 90°
Laminate Thickness = 0.1051 in.
Composite Density = 1.475 gm/cc
Fiber Content: 57.64% by wt, 48.32% by volume
Void Volume = 0.88%

Physical Property	Test Temp. (°F)	Spec. No.	Results	SwRI S3-202
Ultimate Flexural Strength (psi)	RT	C-1-14	169,200	
	RT	C-1-15	161,900	
	RT	C-1-16	157,500	
		Average	162,800	200,000
Flexural Modulus ($\times 10^6$ psi)	RT	C-1-14	18.13	
	RT	C-1-15	18.54	
	RT	C-1-16	16.39	
		Average	17.69	
Flexural Strength-Transverse (psi)	RT	C-1-17	6,215	
	RT	C-1-18	6,446	
	RT	C-1-19	7,145	
		Average	6,602	8,000
Flexural Modulus Transverse ($\times 10^6$ psi)	RT	C 1-17	1.07	
	RT	C-1-18	1.02	
	RT	C-1-19	1.06	
		Average	1.05	
Horizontal Shear Strength (psi)	RT	C-1-21	9,260	
	RT	C-1-22	9,305	
	RT	C-1-23	9,360	
		Average	9,310	14,000

NOTE: Span for longitudinal flexure tests was 3.2 in. or span thickness = 32:1
Span for transverse flexure tests was 2.5 in. or span thickness = 25:1
Quarter point loading and a loading rate of 0.050 in./min was used for for flexure tests. Horizontal shear test span was 0.4 in. with 0.050 in./min loading rate.

both panels had a resin starved appearance. One set of flexural test specimens from these panels was tested using the span/thickness ratios of approximately 32:1 for longitudinal and approximately 25:1 for transverse specimens. Repeat tests on specimens from Panel C-19 with a span of 2.00 inches (span/thickness ratio of 23:1) for both longitudinal and transverse specimens gave a lower strength and modulus for the longitudinal specimens and a slightly higher strength and modulus for the transverse specimens. The 32:1 ± 5% ratio of span/thickness was adopted as standard for all subsequent tests of longitudinal specimens. The span/thickness ratio of 25:1 ± 5% was used for the remainder of the transverse flexural specimens during the process development program. These span/depth ratios were used for all subsequent 10-ply unidirectional acceptance tests. It was obvious at this time that resin bleed-out from both top and bottom surfaces of the lay-up was required to obtain the desired fiber volume and also to eliminate resin poor areas which occur if one surface of the panel is non-bleeding.

The total thickness of the lay-up for Panel C-20 was too great to be contained within one thickness of the Coroprene boundary support (0.125 inch thick) so that a second layer* was used and a 0.020-inch thick shim of aluminum was placed under the layup on the lower aluminum caul plate to reduce the required compression of the boundary support. For Panel C-21, a vent ply (181 glass fabric) was placed on the shim. This was covered with a Mylar sheet which was perforated on 2-inch centers. Two 120 glass bleeder plies were placed on this and covered with a 0.001-inch thick TX-1040 (Teflon coated glass fabric) separator ply. The graphite/epoxy prepreg was then laid up in the normal fashion. The lay-up was covered with TX-1040 separator and six plies of 120 glass bleeder cloth were placed in position. A 0.001-inch film of Mylar was then placed over the lay-up and boundary support with perforations on 2-inch centers. This was covered with a 181 glass vent ply and the upper aluminum caul plate. Total load on the press was maintained at 15 tons during cure. Panels C-22 and C-23 were the same except for the use of additional plies of 120 glass bleeder cloth as indicated in the Table IV.

Although the ply thickness of Panel C-23 was almost 0.009 inch, the mechanical and other physical properties were considered to be satisfactory. This was then adopted as the standard lay-up and cure for the fabrication of all subsequent flat panels. However, when Batch No. OB 6-3 of prepreg was received and Panel C-38 was fabricated for acceptance testing, the ply thickness was less than 0.008 inch and the fiber content by volume was over 65%. Panel C-42 was therefore laid up and cured at a lower pressure with satisfactory results. Subsequent panels

*Bonded to it with contact cement.

TABLE IV

SUMMARY OF TEST RESULTS ON 10 PLY, 0° FIBER ORIENTATION PANELS, 6" X 9"
SwRI Project No. 03-2776 (Contract F33615-70-C-1330)

Material: Courtauld's HTS Graphite Fiber Tow with ERL 2256 Epoxy Resin
Manufactured By: Fiberite Corporation
Date: October 21, 1970

										Average of Three Specimens Per Test								
										Longitudinal Flexure				Transverse Stress				Longitudinal
Panel No.	Prepreg Batch No.	No. of Bleeder Plies(1)		Cure Pressure(2) (tons)	Panel Total Thickness (inch)	Panel Thickness/Ply (inch)	Panel Density (lb/cu.in.)	Fiber Volume (percent)	Void Volume (percent)	Span (inches)	Span/ Depth Ratio	Ultimate Strength (psi)	Modulus (x 10^6 psi)	Span (inches)	Span/ Depth Ratio	Ultimate Strength (psi)	Modulus (x 10^6 psi)	Horizontal Shear Strength (psi)
		Top Only																
C-1	OB 6-1	2		12	0.1051	0.0105	0.0533	48.43	1.26	2.00	19.1	167,280	20.681	2.00	19.1	11,026	1.165	13,670
C-1(3)	OB 6-1	2		12	0.1051	0.0105	0.0533	48.43	1.26	3.20	30.4	162,840	17.839	2.50	23.8	6,602	1.046	13,942
C-19	OB 6-1	4		12	0.0881	0.0088	0.0545	49.73	0	2.80	31.8	170,400	19.585	2.20	24.9	7,779	1.008	13,074
C-19(4)	OB 6-1	4		12	0.0881	0.0088	0.0539(5)	48.23	0	2.00	22.7	155,280	16.317	2.00	22.7	9,316	1.040	-
C-20	OB 6-1	6		15	0.0926	0.0093	0.0547	50.29	0	3.00	32.4	167,420	20.296	2.20	23.8	7,945	1.079	12,907
C-20	OB 6-1	6		15	0.0926	0.0093	0.0541(5)	49.48	0.03	-	-	-	-	-	-	-	-	-
		Top	Bottom															
C-21	OB 6-1	6	2	15	0.0915	0.0092	0.0546	52.66	0.28	2.84	31.1	183,010	19.488	2.22	24.4	9,095	1.071	13,747
C-22	OB 6-1	8	2	15	0.0886	0.0089	0.0550	54.02	0.14	2.84	32.1	187,610	20.977	2.22	25.1	7,591	1.049	13,050
C-23	OB 6-1	10	4	15	0.0870	0.0087	0.0550	55.88	0.70	2.75	31.6	184,010	19.796	2.15	24.8	7,847	1.029	13,506
C-38	OB 6-3	10	4	15	0.0756	0.0076	0.0569	65.43	0.73	2.375	31.5	201,180	26.368	2.00	26.5	5,000	1.460	13,489
C-42	OB 6-3	10	4	12	0.0878	0.0088	0.0553	56.81	0.58	2.75	31.4	173,710	25.890	2.00	22.8	9,100	1.384	13,330
C-65	OB 6-4	9	5	12	0.0915	0.0092	0.0556	58.71	0.69	3.00	32.8	166,535	19.893	*	*	*	*	*
C-65	OB 6-4	9	5	12	0.0915	0.0092	0.0556	58.71	0.69	2.00	21.9	131,420	14.823	*	*	*	*	*

Notes: (1) Bleeder cloth is 0.005 inch thick 120 glass fabric.
(2) Cure pressure is the total load applied to the lay-up and boundary support. Boundary support is made of Coroprene, 0.125 inch thick by 2 inches wide on all sides of the 6 inch by 9 inch lay-up. Two layers or 0.250 inch thick boundary support was used for Panels C-20 through C-65 and a 0.020 inch thick shim was used under the lay-up to reduce the compression of the Coroprene. It is not possible to determine the distribution of the load between the lay-up and boundary support; however, the loads were intended to provide 100 psi on the lay-up for C-1 and C-19; 200 psi for C-20 through C-38; and 175 psi for C-42 and C-65.
(3) Panel C-1 was not inspected by ultrasonic through transmission prior to being cut for initial tests. When the remaining piece was ultrasonically inspected, the cut edge was not coated to prevent water infiltration. Thus, these tests at span to thickness ratios of 32:1 for longitudinal and 25:1 for transverse flexural tests may be lower than the previous results because of water infiltration.
(4) Initial tests of C-19 utilized the longer span to thickness ratios listed in Note (3). Repeat tests at a span of 2.0 inches indicate that a much lower longitudinal flexure strength and modulus and slightly higher transverse flexural strength and modulus are measured.
(5) Repeat tests for density, fiber content, and void content of Panels C-19 and 20 used only two specimens, each.

*Not tested because specimens cut in wrong fiber direction.

fabricated with material from this batch were then cured at the lower pressure. Panel C-65 was the material acceptance test panel for Batch No. OB 6-4 and was found to be satisfactory with the lower pressure cure used for Panel C-42. During the cutting of specimens from this panel (C-65), the piece from which the transverse flexure and interlaminar shear specimens were to be cut was turned the wrong way and the flexure specimens were cut in the longitudinal direction while the shear specimens were cut in the transverse direction. The entire panel was cut into specimens so that no replacement specimens were available and no transverse flexure or shear tests could be made. However, in order to confirm the difference in longitudinal flexure results between a specimen at a 2-inch span as compared to the 3-inch span (32:1 span to thickness ratio), the shorter specimens were tested and the results shown in the table. Both longitudinal flexure strength and modulus were much lower at the 2-inch span.

Copies of the certification sheets for Batch Nos. OB 6-1, -3 and -4 are included as Tables V, VI and VII.

c. Final Flat Panel Fabrication

The final group of flat panels which were to be used for preparation of specimens for Tasks I, II and III was fabricated as listed in Table VIII. The panels actually used for subsequent testing in these tasks were C-24, -26, -27, -39, -40, -45, -48, -49, -50, -53, -54, -55, -57, -60, -61, -63, -64, -67 and -68. Panel C-41 was to be used, but the quality control tests (see subsection d below) indicated that the panel was of poor quality and Panel C-67 was fabricated as a replacement for C-41.

The 4-ply, 90° panels fabricated for transverse tensile strength tests were found to be unsatisfactory. The specimens became warped during cure of the adhesive used to attach load pads. Panels C-61 and C-62 were fabricated as substitutes for Part Nos. 4-5 and 5-7 Tension Test Panels. Panel C-68 was later fabricated as a replacement for C-62 which had a ply thickness of 0.0099 inch which was judged to be too high and was therefore rejected as a test specimen panel.

The cure pressure on the lay-up was calculated for 200 psi on panels through C-41. However, the material acceptance test panel for prepreg Batch OB 6-3 (C-38) had a ply thickness less than 0.008 inch. Panel C-42 was then fabricated with a cure pressure of 175 psi which gave satisfactory results as described in the previous section. Panels through C-65 were then cured at a calculated pressure on the lay-up of 175 psi. Panel C-65 was the material acceptance test panel for Batch No. OB 6-4 of the prepreg material. Although the test results on this panel were considered to be acceptable, it was decided to increase the cure pressure to 200 psi for all subsequent panels fabricated with this batch of material (C-66 through C-69) to improve the physical and mechanical properties.

Panels C-58 and C-59 were laid up with pieces of TX-1040 Teflon treated glass cloth of various sizes and shapes placed between the 90° plies at the midpoint of the lay-up in the pattern shown in Figure 2. The charts of the through transmission ultrasonic inspection of these panels are shown in Figures 3 and 4. The distortion of the chart indication of the inclusions is evidently caused by drift and/or excessive "dead-band" width in the X-Y recorder. Both the 4-ply and the 12-ply panels produced a satisfactory chart of the inclusions at a setting of 3db on the ultrasonic inspection instrument.*

Figure 5 presents the panel lay-up technique and curing equipment used for the graphite/epoxy composite panels. Photo A shows the final top bleeder plies being placed on a 16 × 20-inch panel which utilizes a Coroprene rubber dam to contain the resin during the flowing stage of curing. In photo B the 20 × 24-inch 50 ton M&N hot platen press and temperature recorder/controllers used in curing the panels are shown.

d. Quality Control

The quality control procedure followed for all panels included a visual inspection for flaws when the panel was removed from the lay-up plate followed by measurement of the thickness at a number of points around

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*Sperry, Model UM 721.

TABLE V

CERTIFICATION SHEET FOR BATCH OB 6-1

CERTIFICATION

Date: 6-4-70

ATTENTION: Mr. Sam Winegardner

Gentlemen:

We certify that Fiberite Hy-E-1317-B straight tape ordered on your Purchase Order 976 SW has been tested in accordance with the applicable specification procedures and found to possess the following properties, therefore meeting the requirements of SwRI-S3-202 specification. (Any exceptions are noted on reverse side.)

SPECIFICATION LIMITS

Quantity Shipped On 6-4-70		15#		
Lot No.		OB 6-1		
[illegible] Sheet No.		1-10	11-20	21-31
~~Tape Size, Inches~~ Sheets		12" x 45"		
Resin Solids, %		41.2	43.3	43.2
Volatile Content, %		2.3	2.3	2.8
Laminate Flow, %@ p.s.i.		—	—	—

	TEST METHOD A.S.T.M.	LP-406				
Specific Gravity	D-792	5011				
Tensile Strength (p.s.i.)	D-638	1011				
Tensile Modulus (10^6 p.s.i.)	D-638	1011				
Tensile Elongation (%)	D-638	1011				
Flexural Strength (p.s.i.)	D-790	1031.1				
Flexural Modulus (10^6 p.s.i.)	D-790	1031.1				
Compression Strength (p.s.i.)	D-695	1021				
Acetone Extraction (%)	D-494	7021				
Hardness						
Spectrum No.						
Gel Time (Min.) @ 170° C				2.5	3.0	3.5

E.W. Hemmelman

17 E. W. HEMMELMAN
Manager, Quality Control

TABLE VI

CERTIFICATION SHEET FOR BATCH OB 6-3

CERTIFICATION

Date: September 1, 1970

ATTENTION: Mr. Sam. B. Winegardner

Gentlemen:

We certify that Fiberite Hy-E-1317-B straight tape ordered on your Purchase Order 976SW has been tested in accordance with the applicable specification procedures and found to possess the following properties, therefore meeting the requirements of SwRI-S3-202 specification. (Any exceptions are noted on reverse side.)

SPECIFICATION LIMITS

Quantity Shipped On 9-1-70		14.9#		
Lot No.		OB6-3		
Roll No.		2-10	11-20	21-28
~~Tape Size, Inches~~ sheets		12"x45"		
Resin Solids, %		42.5	42.7	44.1
Volatile Content, %		1.7	1.5	1.9
Laminate Flow, %@ p.s.i.		-	-	-

	TEST METHOD A.S.T.M.	LP-406		
Specific Gravity	D-792	5011		
Tensile Strength (p.s.i.)	D-638	1011		
Tensile Modulus (10^6 p.s.i.)	D-638	1011		
Tensile Elongation (%)	D-638	1011		
Flexural Strength (p.s.i.)	D-790	1031.1		
Flexural Modulus (10^6 p.s.i.)	D-790	1031.1		
Compression Strength (p.s.i.)	D-695	1021		
Acetone Extraction (%)	D-494	7021		
Hardness				
Spectrum No.				

E.W. Hemmelman

18 E. W. HEMMELMAN
Manager, Quality Control

WFCo. 1144-9156

TABLE VII

CERTIFICATION SHEET FOR BATCH OB 6-4

Date: 12-7-70

ATTENTION: Mr. Sam B. Winegardner

Gentlemen:

We certify that Fiberite Hy-E-1317-B sheets ordered on your Purchase Order 976-SW has been tested in accordance with the applicable specification procedures and found to possess the following properties, therefore meeting the requirements of SwRI-S3-202 specification.

Quantity Shipped On 12-7-70	16.9#
Lot No.	OB-6-4
Sheet No.	1-32
Sheet Size, Inches	12" x 45"
Resin Solids, %	39.0
Volatile Content, %	5.4
Laminate Flow, %@ p.s.i.	——
Specific Gravity	
Tensile Strength (p.s.i.)	
Tensile Modulus (10^6 p.s.i.)	
Flexural Strength (p.s.i.)	
Flexural Modulus (10^6 p.s.i.)	
Compression Strength (p.s.i.)	
Horizontal Beam Shear (p.s.i.)	Shelf life: 6 weeks @ 0° F 1 day @ 70° F

E.W. Hemmelman

19 E. W. HEMMELMAN
Manager, Quality Control

WFCo.-1570-11561

TABLE VIII

FABRICATION OF FLAT PANELS

Panel No.	Part No. 03-2776-01-	Size* (in.)	No. of Plies	Thickness (in.)	Fiber† Orientation	Remarks
C-24	4-3	15 x 3	4	0.0322	$[0]_{4T}$	
C-25	4-5	3 x 15	4	0.0318	$[90]_{4T}$	
C-26	4-7	15 x 3	4	0.0318	$[0/90]_S$	
C-27	4-9	3 x 15	4	0.0306	$[90/0]_S$	
C-28	4-11	15 x 3	12	0.1223	$[0]_{12T}$	
C-29	4-13	3 x 15	12	0.1211	$[90]_{12T}$	
C-30	4-15	15 x 3	12	0.1174	$[0/90_2/0]_{3T}$	
C-31	4-17	3 x 15	12	0.1174	$[90/0_2/90]_{3T}$	
C-32	5-3	10.5 x 8	3	0.0306	$[0]_{3T}$	
C-33	5-7	8 x 10.5	4	0.0369	$[90]_{4T}$	
C-34	5-5	10.5 x 8	12	0.1114	$[0]_{12T}$	
C-35	5-9	8 x 10.5	12	0.1176	$[90]_{12T}$	
C-36	5-7	8 x 10.5	4	0.0396	$[90]_{4T}$	
C-37	5-11	10.5 x 15	4	0.0381	$[90/0]_S$	
C-38	X	9 x 6	10	0.0756	$[0]_{10T}$	Material Acceptance Test Panel
C-39	5-11	15 x 10.5‡	4	0.0299	$[0/90]_S$	
C-40	5-13	10.5 x 12	12	0.0974	$[90/0_2/90]_{3T}$	
C-41	5-13	10.5 x 12	12	0.1018	$[90/0_2/90]_{3T}$	
C-42	X	9 x 6	10	0.0878	$[0]_{10T}$	Process Improvement Test Panel
C-43	4-11	15 x 3	12	0.1254	$[0]_{12T}$	
C-44	4-13	3 x 15	12	0.1284	$[90]_{12T}$	
C-45	4-15	15 x 3	12	0.1018	$[0/90_2/0]_{3T}$	
C-46	4-17	3 x 15	12	0.1102	$[90/0_2/90]_{3T}$	
C-47	5-3	10.5 x 8	3	0.0248	$[0]_{3T}$	
C-48	5-11	10.5 x 15	4	0.0342	$[90/0]_S$	
C-49	5-5	10.5 x 8	12	0.0976	$[0]_{12T}$	
C-50	5-9	8 x 10.5	12	0.1021	$[90]_{12T}$	
C-51	5-7	8 x 10.5	4	0.0291	$[90]_{4T}$	
C-52	5-7	8 x 10.5	4	0.0328	$[90]_{4T}$	
C-53	4-11	15 x 3	12	0.1078	$[0]_{12T}$	
C-54	4-13	3 x 15	12	0.1039	$[90]_{12T}$	
C-55	4-17	3 x 15	12	0.0978	$[90/0_2/90]_{3T}$	
C-56	6-3	20.5 x 8.5	4	0.0320	$[0/90_2/0]_T$	
C-57	6-5	20.5 x 16	12	0.1058	$[0/90_2/0]_{3T}$	
C-58	Y	8 x 5	4	0.0330	$[0/90_2/0]_T$	Ultrasonic Test Panel with Unbonds
C-59	Y	8 x 5	12	0.1143	$[0/90_2/0]_{3T}$	Ultrasonic Test Panel with Unbonds
C-60	6-5	20.5 x 16	12	0.1167	$[0/90_2/0]_{3T}$	
C-61	4-13	3 x 15	12	0.1191	$[90]_{12T}$	Substitute for Part No. 4-5 Tension Test
C-62	5-9	8 x 10.5	12	0.1184	$[90]_{12T}$	Substitute for Part 5-7 Tension Test
C-63	5-11	10.5 x 15	4	0.0358	$[90/0]_S$	
C-64	5-11	10.5 x 15	4	0.0364	$[90/0]_S$	
C-65	X	9 x 6	10	0.0915	$[0]_{10T}$	Material Acceptance Test Panel
C-66	X-1	10.5 x 12	12	0.1134	$[0]_{12T}$	Special Test Panel
C-67	5-13	10.5 x 12	12	0.1028	$[90/0_2/90]_{3T}$	Replacement for C-41
C-68	5-9	8 x 10.5	12	0.1102	$[90]_{12T}$	
C-69	Z	10 x 12	18	0.1655	$[0]_{18T}$	AFML Compression Test Panel

*Surface ply fibers are oriented in the direction of the first dimension listed.

†Fiber orientation is with respect to the long axis of the panel.

‡Plies were laid up in reverse order resulting in specimens having 90/0/0/90 fiber orientation.

the perimeter of the panel and at least one-half inch in from the edge. An average of these thickness measurements was recorded as the nominal panel thickness and these values are included in Tables I, IV and VIII in the preceding sections.

The first panels fabricated (Table I) were fabricated during the time that the ultrasonic inspection facility was inoperative. Thus they were not examined except for Panel C-1 which had previously been cut for acceptance test specimen (see Section a above). Panels C-19 through C-64 were inspected in the through-transmission ultrasonic facility. The X-Y recorder then became inoperative and the remainder of the panels were not inspected. The

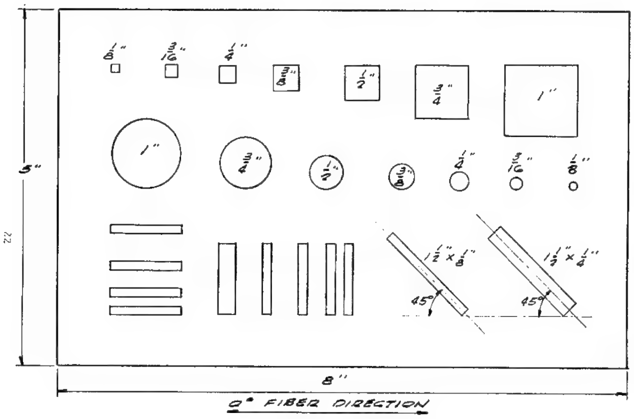


FIGURE 2. LAYOUT FOR INCLUSIONS PLACED IN PANELS C-58 AND C-59

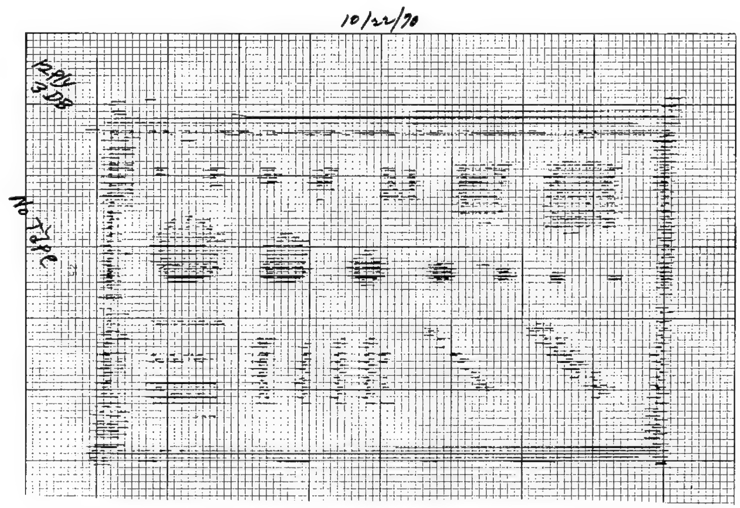


FIGURE 3. ULTRASONIC SCAN OF PANEL C-58

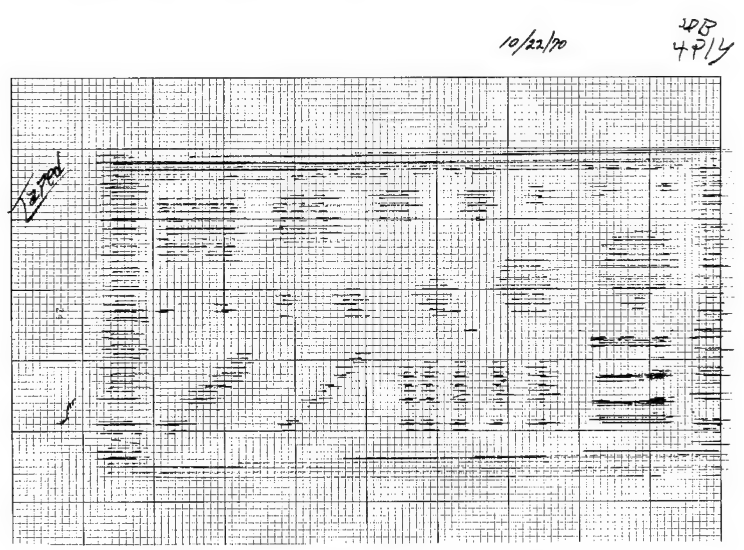
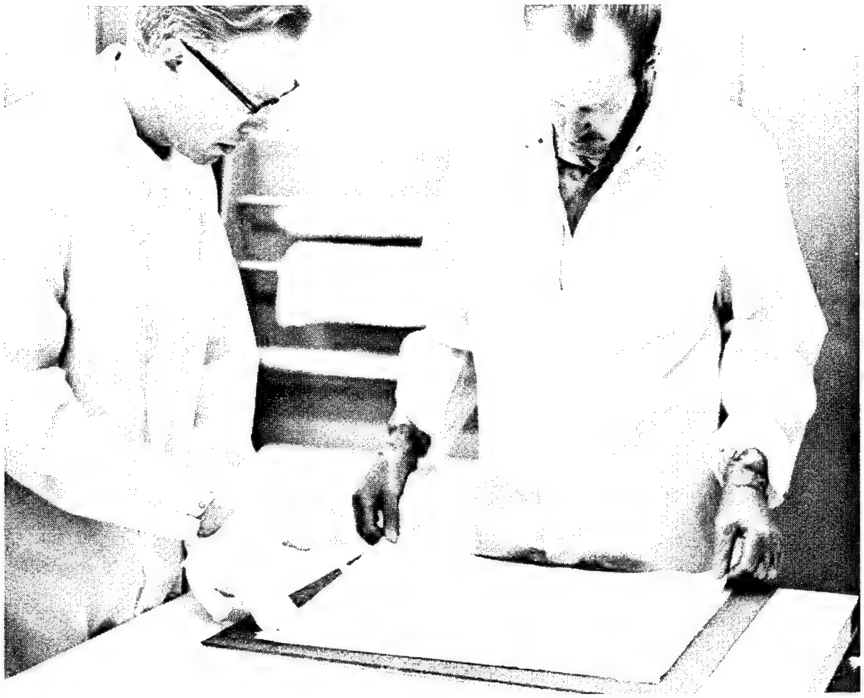
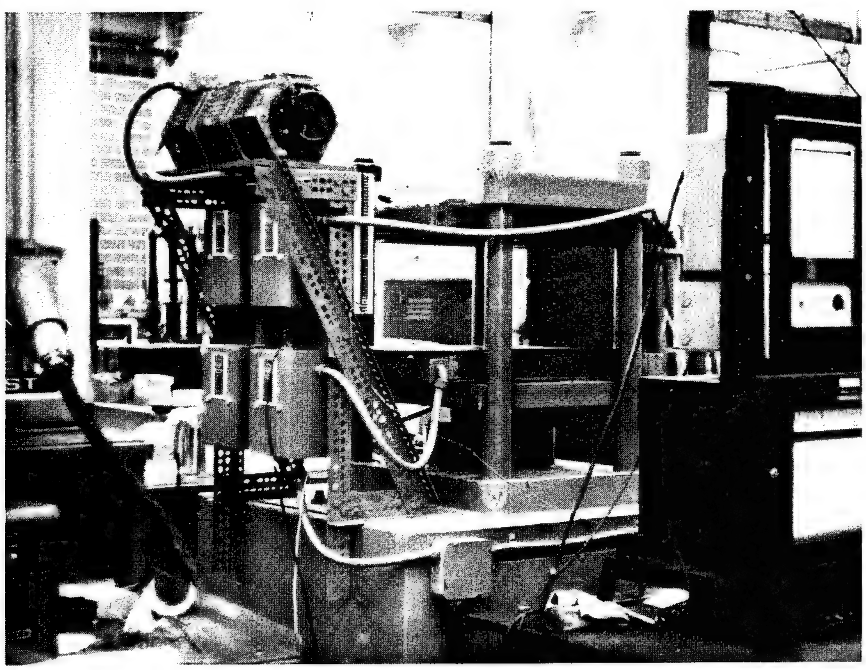


FIGURE 4. ULTRASONIC SCAN OF PANEL C-59



A. Panel Layup



B. 50-Ton M&N Hot Platen Curing Press

FIGURE 5. PANEL PROCESSING

ultrasonic inspection was not used as a criterion for rejection of any panel, but was considered in conjunction with the flexural and interlaminar shear tests and determinations of density, fiber content, and void volume described below.

Each panel which was judged to be acceptable on the basis of inspections described above was cut into test specimen blanks. A diamond saw was used to cut the panels on a horizontal milling machine with automatic control of the table feed speed. Each specimen blank was thus cut to its final dimensions within the tolerance specified in the specimen preparation instructions*, and no further milling or grinding was required to achieve straight and parallel edges. The specimens cut from each panel included those for longitudinal and transverse flexure tests, short beam horizontal shear tests, and specific gravity/fiber content determinations. These constituted the principal quality control tests for all panels used for tests in Tasks I, II and III. Only one panel, C-41, was rejected for subsequent testing. Panel C-67 was fabricated as a replacement for C-41. Results of these tests are given in Table IX.

One other panel, C-39, could have been rejected on the basis of the wide variation of the test results in longitudinal flexure and the ultrasonic inspection, Figure 6. However, it was submitted for characterization of the panel in static tension, and subsequent incremental tension loading. Although a sizeable variation was obtained in the static tension tests, the specimens used in the incremental tension loading appear to be of acceptable quality as shown by the stress-strain curves in Figure II.47, Appendix II.7. The ultrasonic inspection chart of Panel C-41 which was rejected is shown in Figure 7 for comparison with that of C-39 (Fig. 6). It is believed that the orientation of the surface fibers is the principal cause of the difference in these two charts. The surface fibers are perpendicular to the direction of scan for C-39 and parallel for C-41. This is most noticeable in a scan of Panels C-49 and C-50, Figure 8, which were laid up and cured together. These are unidirectional, 12-ply panels and the only difference is the fiber orientation with respect to the long axis of the panel. A later ultrasonic inspection of C-49 with the direction of scan parallel to the fiber direction is shown in Figure 9. This effect is again illustrated in Figure 10 which is the chart for Panels C-45, C-53, C-54 and C-55 which were all 12 plies in thickness, but had different fiber orientations. The surface fibers of C-45 and C-53 were perpendicular to the direction of scan, whereas the surface fibers of C-54 and C-55 were parallel to the direction of scan. The effect of surface fiber orientation with respect to ultrasonic scan direction was not investigated in this program, and because it is not fully understood the ultrasonic inspection was not considered a major quality control test.

3. TUBE FABRICATION

a. Process Development

Initial attempts to fabricate a composite tube utilized glass fabric/epoxy prepreg. The first trial utilized the Cure Mold #1 (Drawing No. 03-2776-01-1, -2, Appendix IV). This attempt was not successful and the inner metal sleeve of the mold was damaged during removal of the tube. The rubber sleeve of the expandable inner mandrel was also too thick (1/16 inch) which had reduced the space available in the mold for the layup and bleeder cloth. The mold design was altered to use a smaller diameter inner sleeve and these modified dimensions are shown in the drawing. High temperature silicone rubber tubing was ordered in a 1/32 inch wall thickness.

A second attempt to fabricate a 4-ply glass fabric/epoxy tube using an aluminum tube as a mandrel and covering the layup with a vacuum bag was also unsatisfactory. The wrapping of the prepreg evidently was not sufficiently tight. Although the vacuum applied to the layup was not augmented by external pressure, the tube was compressed in such a way that a wrinkle was formed along one side of the tube. No bleed out of resin occurred. This test seems to confirm the desirability of the expandable inside mandrel system for fabricating tubes.

The silicone rubber tubing for the expandable mandrel in the tube fabrication tool when received was found to have an average thickness of 3/64 inch. This is the result of tolerance control on the thickness of tubing of this size (3/4 inch I.D.). The laminated tube layup was thus limited to a thickness of four plies with a maximum of three bleeder plies and the separator cloth. Another problem introduced by the greater thickness of the pressure bag was a tendency for the material to form a wrinkle where it was folded inside the inner sleeve to seal against the end caps. This was minimized by presealing the pressure bag to the metal inner sleeve with RTV† silicone sealant. A rubber

*See Appendix I, Specification SwRI S3-401.

†Trade name for Dow Corning room temperature vulcanizing (curing) material.

TABLE IX

QUALITY CONTROL TEST RESULTS

Specimen No.*	Fiber Orientation	Longitudinal Flexure σ_{ult}	Longitudinal Flexure E	Transverse Flexure σ_{ult}	Transverse Flexure E	Interlaminar Shear σ_{ult}	Fiber Content Volume %	Density lb/cu. in.	Void Volume Volume %
TASK I									
241	$[0]_{4T}$	261.5	29.27	9.91	1.85	9.87			
242		243.4	29.97	9.01	1.87	8.86			
243		205.8	28.33	12.08	1.82	10.73			
Average		236.9	29.19	10.33	1.85	9.82	65.41	0.0570	3.57
471	$[0]_{3T}$	274.3	12.62	8.26	0.65	10.24			
472		295.1	14.22	9.32	0.69	7.22			
473		265.5	12.66	8.81	0.64	8.14			
Average		278.3	13.17	8.80	0.66	8.53	64.75	0.0573	2.88
491	$[0]_{12T}$	177.6	21.85	7.50	1.50	14.76			
492		192.2	22.34	8.07	1.49	15.15			
493		182.2	24.47	7.30	1.56	14.64			
Average		184.0	22.89	7.62	1.52	14.85	61.87	0.0564	3.39
531	$[0]_{12T}$	158.1	22.55	8.28	1.49	14.30			
532		166.7	22.17	8.41	1.53	14.25			
533		165.1	22.64	9.78	1.50	13.88			
Average		163.3	22.45	8.82	1.51	14.14	51.91	0.0546	2.67
501	$[90]_{12T}$	185.4	21.53	7.07	1.25	14.68			
502		185.4	21.69	8.29	1.35	13.70			
503		196.2	20.99	7.79	1.37	14.41			
Average		189.0	21.40	7.72	1.32	14.26	61.21	0.0563	3.35
541	$[90]_{12T}$	130.1	21.40	7.47	1.46	14.42			
542		170.4	18.74	7.65	1.48	14.22			
543		177.0	20.77	8.41	1.47	13.99			
Average		159.2	20.30	7.84	1.47	14.21	56.18	0.0554	2.89
611	$[90]_{12T}$	138.5	11.96	9.39	0.98	13.66			
612		131.2	13.08	7.01	0.96	13.68			
613		139.0	14.12	6.29	0.94	13.92			
Average		136.2	13.05	7.56	0.96	13.75	53.97	0.0546	0.71
Panel C-68 was not tested for flexure and shear							56.39	0.0551	0.82
TASK II									
261	$[0/90]_S$	137.3	25.32	124.30	4.51	7.52			
262		104.9	23.64	136.10	4.49	3.25			
263		157.3	25.05	133.40	4.50	8.02			
Average		133.2	24.67	131.30	4.50	6.26	67.24	0.0575	3.39
631	$[0/90]_S$	197.3	10.42	100.50	2.33	6.52			
632		163.0	10.42	112.60	2.52	5.60			
633		169.1	11.54	113.20	2.58	5.61			
Average		176.5	10.79	108.80	2.48	5.91	61.58	0.0562	0.11
641	$[0/90]_S$	166.9	10.14	105.70	2.42	5.89			
642		175.2	10.72	101.80	2.09	6.44			
643		141.1	10.47	104.00	2.53	5.04			
Average		161.1	10.44	103.80	2.35	5.79	57.55	0.0557	0.04
271	$[90/0]_S$	170.3	24.77	89.10	3.09	-			
272		173.4	26.44	101.50	4.19	6.14			
273		184.8	27.01	76.70	4.12	4.25			
Average		176.2	26.07	89.10	3.80	5.20	64.03	0.0570	3.22
391	$[90/0]_S$	76.5	8.36	75.93	2.60	3.50			
392		115.4	12.67	92.64	2.53	3.36			
393		206.7	13.78	96.66	2.20	-			
Average		132.9	11.60	88.41	2.44	3.43	59.75	0.0559	3.34
481	$[90/0]_S$	114.2	10.72	62.40	2.25	3.11			
482		114.0	10.90	37.00	2.06	3.38			
483		164.5	16.32	64.70	2.15	2.68			
Average		130.9	12.65	54.70	2.15	3.06	55.45	0.0560	1.56
Panel C-56 was not tested for flexure and shear							60.39	0.0557	0.98
TASK III									
401	$[0/90_2/0]_{3T}$	132.6	10.27	98.44	12.00	8.50			
402		131.0	9.95	124.50	12.04	7.86			
403		129.4	9.35	120.70	12.47	8.37			
Average		131.0	9.86	114.50	12.17	8.24	55.71	0.0552	3.04
411	$[0/90_2/0]_{3T}$	62.7	12.59	67.22	10.75	8.08			
412		56.9	13.04	66.67	10.82	6.66			
413		75.3	13.49	72.74	10.14	6.61			
Average		65.0	13.04	68.88	10.57	7.12	52.43	0.0562	0.01
451	$[0/90_2/0]_{3T}$	115.0	13.41	68.50	10.14	7.50			
452		114.7	13.22	88.80	11.59	5.96			
453		96.0	13.32	97.10	10.75	7.70			
Average		108.6	13.32	84.80	10.83	7.05	49.37	0.0546	1.74
671	$[0/90_2/0]_{3T}$	111.4	8.78	109.70	7.52	7.24			
672		94.1	9.06	97.50	7.38	10.74			
673		101.2	8.74	108.70	7.51	9.28			
Average		102.2	8.86	105.30	7.47	9.09	56.34	0.0552	0.63
551	$[90/0_2/90]_{3T}$	113.3	14.67	112.90	12.05	8.16			
552		113.8	13.75	119.50	12.60	7.86			
553		112.4	14.34	115.50	12.00	8.50			
Average		113.2	14.25	116.00	12.22	8.17	56.95	0.0554	3.16
Panels C-57 and C-60 were not tested for flexure and shear									
C-57							56.61	0.0551	0.92
C-60							51.66	0.0542	0.68

*First two digits of the specimen number indicate the panel number.

TEST OPERATOR Buckley
DATE 10/22/90

PANEL NUMBER C-39 4PLY

PRINCIPAL FIBER ORIENTATION.

SENSITIVITY SETTING JB-3

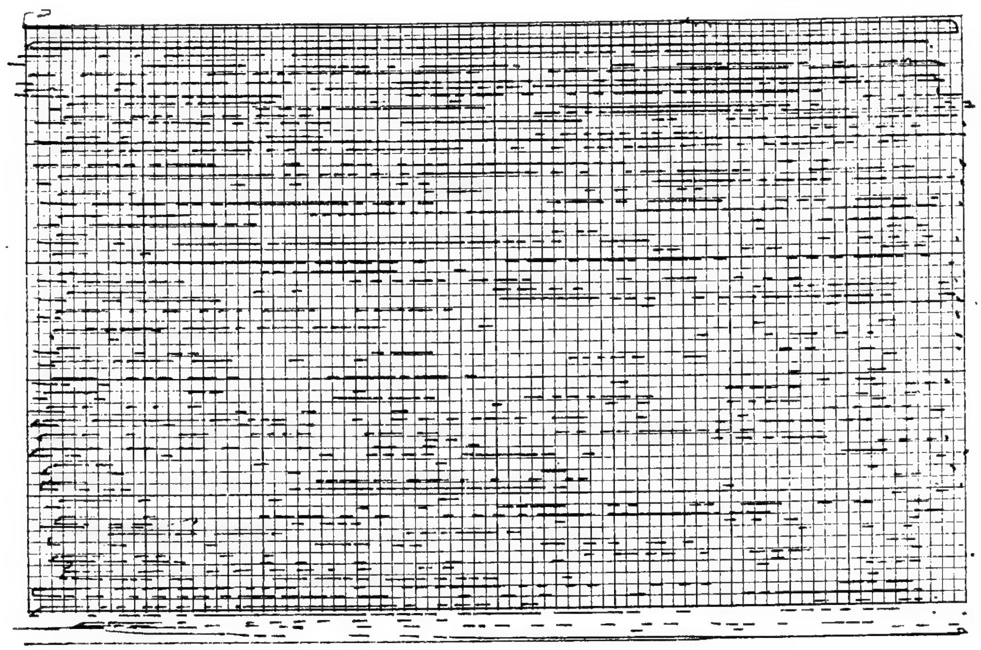


FIGURE 6. ULTRASONIC SCAN OF PANEL C-39

TEST OPERATOR Buckley
DATE 10/26/90

PANEL NUMBER C-41 12PLY 0/90/0

PRINCIPAL FIBER ORIENTATION.

SENSITIVITY SETTING JB 3 Below Max. Sig.

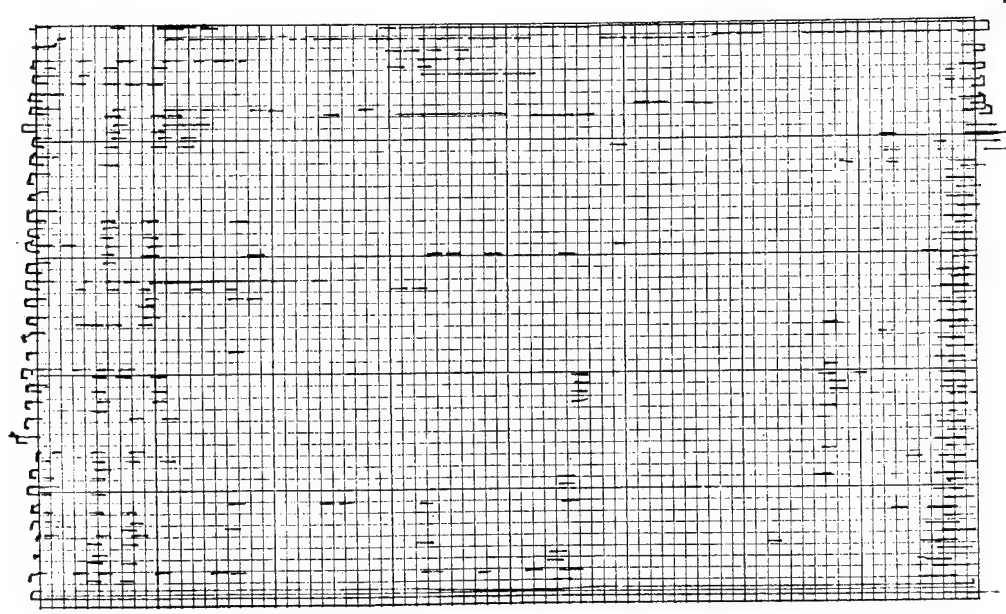


FIGURE 7. ULTRASONIC SCAN OF PANEL C-41

ULTRASONIC INSPECTION RECORD

TEST OPERATOR Buckley

DATE 10/14/70

PANEL NUMBER C-50 and C-49

PRINCIPAL FIBER ORIENTATION

SENSITIVITY SETTING 3 db

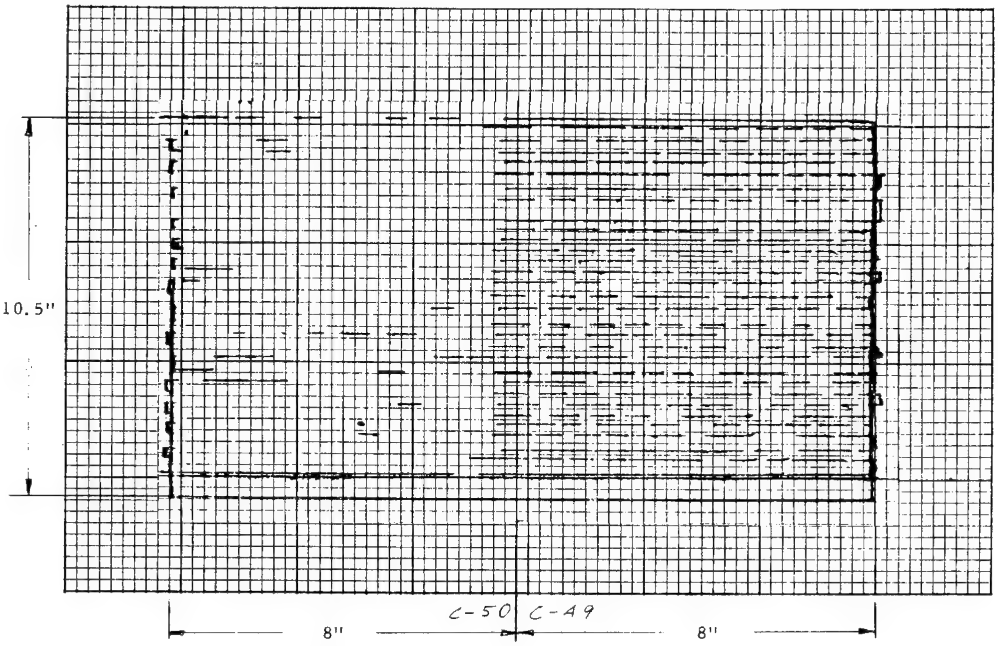


FIGURE 8. ULTRASONIC SCAN OF PANELS C-49 AND C-50

ULTRASONIC INSPECTION RECORD

TEST OPERATOR Buckley

DATE 10/28/70

PANEL NUMBER C-49 0° 12P/Y

PRINCIPAL FIBER ORIENTATION

SENSITIVITY SETTING DB-3

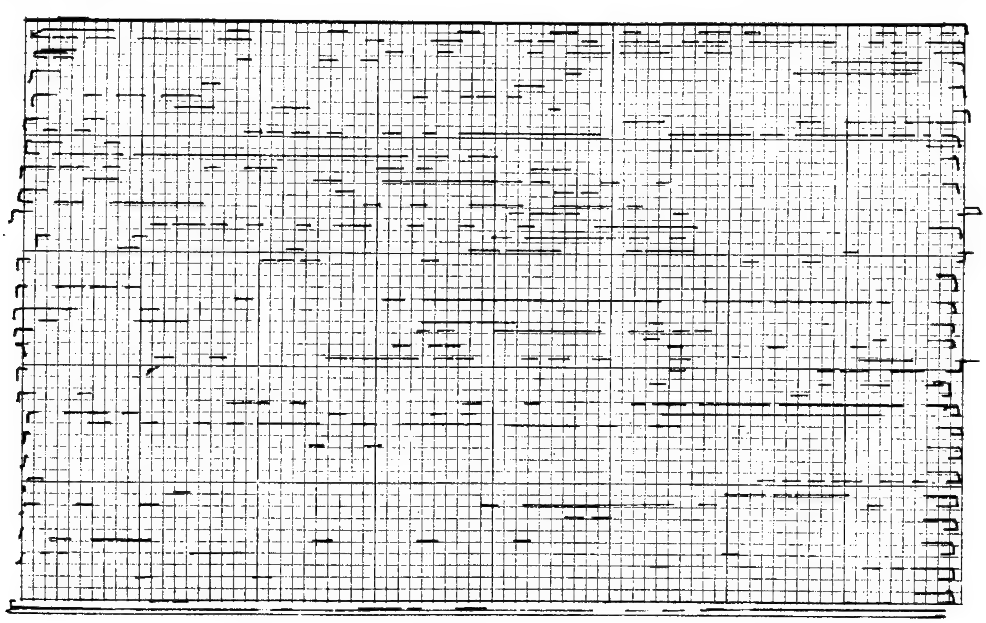


FIGURE 9. ULTRASONIC SCAN OF PANEL C-49

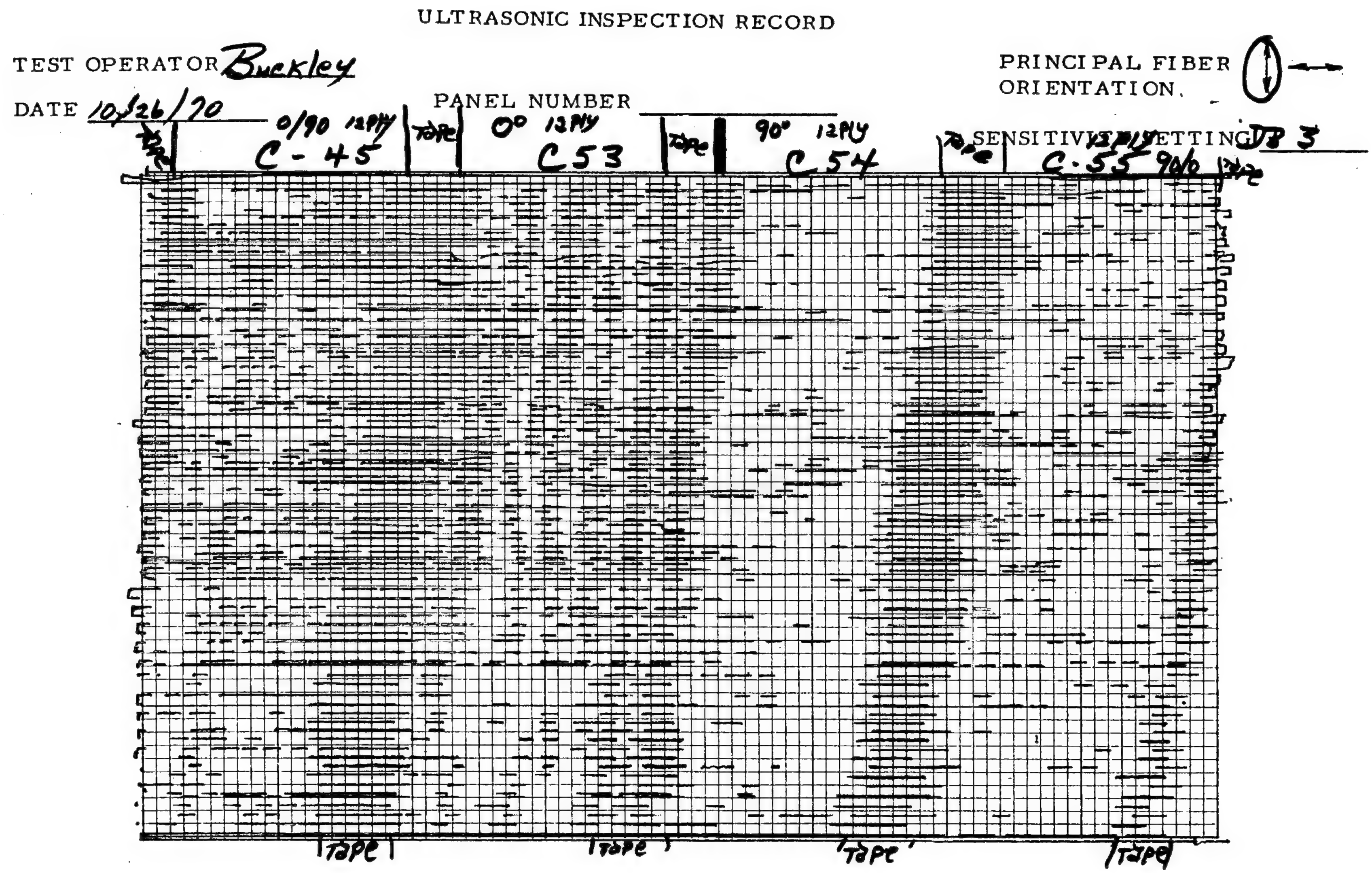


FIGURE 10. ULTRASONIC SCAN OF PANELS C-45, -53, -54 AND -55

stopper was used to apply pressure to the tubing folded inside the tapered ends of the inner sleeve while the sealant cured for 24 hours prior to use. This also prevented formation of a wrinkle in the pressure bag in the area where it seals against the end caps.

The layup process employs hand rolling of the materials on the expandable, silicone rubber tube covered, perforated mandrel. Dry 120 glass fabric was used as bleeder and was wrapped on the mandrel first. This was followed by a layer of TX-1040 Teflon treated glass fabric separator. Three or four plies of graphite/epoxy prepreg of correct length were layed out flat in a staggered manner and then wrapped over the bleeder with the fiber axis at 0° to the tube axis. This was covered with another layer of separator cloth for the first eight trials. The layup was placed inside the outer mold sleeve and the end caps put into place and tightened by means of the tie rod and nut. The assembled mold was placed inside the air-circulating oven and the pressurization fitting attached to a pipe extending through a port in the oven wall. Lab air was used for pressurization of the first three trials which limited the pressure to 100 psi. Poor results were achieved in these trials with very little resin bleed-out. A high pressure nitrogen cylinder was then attached through a pressure regulator and a pressure of 200 psi was used for the next five trials. The tubes are numbered consecutively in the chronological order of fabrication with the prefix CT. The letter C designates the material, graphite/epoxy, and the T is used to distinguish the tube number from the numbering system for flat panels.

Tube No. CT-4 was cured using Mylar film instead of the TX-1040 Teflon treated glass cloth for separator. The film between the prepreg and the bleeder cloth was perforated approximately every inch along the length and at 90° around the circumference. It was thought that this would give a smooth finish to both inner and outer surfaces of the tube; however, the Mylar adhered very strongly to the cured tube and very little bleed-out occurred. This was a four-ply 0° layup.

CT-5 was laid up with three plies again using the TX-1040 separator cloth. Expansion of this tube resulted in opening of gaps in the sides at several points. This was probably the result of applying the full 200 psi pressure to the mandrel before heating the mold. The layup did not expand sufficiently to fully contact the outer sleeve of the mold.

CT-6 was then laid up with only two plies of prepreg. Pressure was not applied until the mold reached 170°F (temperature at which resin starts to flow) and the layup expanded to complete contact with the outer sleeve. Since the outer surface of the layup was covered with TX-1040 separator cloth, the cured tube has the impression of this cloth on its surface. The tube was extremely fragile and split lengthwise when removed from the mold.

CT-7 and -8 were laid up with four plies at 0° and were cured in the same manner as CT-6 with pressurization only after the mold reached 170°F. These were cured on a shortened cycle of one hour at 180°F and two hours at 300°F in order to speed up the process development tests. Both of these tubes achieved full expansion as shown by imprint of the separator cloth on the outside surface of the tubes; however, the amount of resin bleed-out was still less than desired.

The outer cover of separator was eliminated for CT-9 and all tubes thereafter through CT-17 so that the tube would expand against the chrome plated inner wall of the outer mold sleeve. This surface was thoroughly coated with Ram-Part 87-X76 release agent. The layup was fully expanded against the outer sleeve, resulting in a smooth, seamless, resin rich outer surface on the tube. Resin bleed-out was still inadequate with the tube wall thickness measuring 0.010 to 0.012 inch/ply. Samples of the tube were cut from each end and submitted for specific gravity and fiber content determinations. These gave a density of 0.0536 lb/cu in. and a fiber volume of 47.9% for tube CT-9.

Tubes CT-10 through CT-17 were fabricated in the same manner as CT-9 except that the pressure on the expandable mandrel was increased to 300 psi and the hold time at 180°F was omitted. The increased pressure was intended to improve resin bleed-out. The elimination of the 180°F hold time was based on the fact that the gel time for the ERL-2256 resin is only two to three minutes and no bleed-out occurs after the resin has gelled. These tubes were for process development only and were not to be used as test specimens. Tubes CT-10 through -13 did not expand fully and CT-14 through -17 did expand against the outer mold with essentially the same processing conditions. Tubes CT-14 through -17, although fully expanded, did have small areas on the outer surface where air bubbles were evidently trapped during expansion. Because of this it was decided to put a vacuum connection in the side of

the outer sleeve near one end. This vacuum connection is located at the top of the layup when the mold is put into the oven.

Tube CT-18 was laid up for a $[0/90]_S$ fiber orientation. This was the first trial with a vacuum applied to the mold and a schedule of gradually increasing pressure was applied as the mold heated from 150°F to 180°F. However, the pressure bag broke as the mold reached a temperature of 175°F and the layup failed to bond properly.

Tubes CT-19 through -23 were four-ply, 0° fiber orientation layups which continued to utilize a stepwise increase in pressure on the inside of the expandable mandrel and a vacuum between the mold and the composite tube layup. For Tubes CT-19, -20, and -21 the vacuum was started at a mold temperature of 100°F followed by introduction of pressure to the mandrel in 50 psi increments at 5° increments of temperature from 150° to 175°. This gave a final pressure of 300 psi which was maintained throughout the two hour cure at 300°F. Samples from CT-20* were submitted for specific gravity and fiber content determinations and these gave values of 0.0527 lb/cu in. and 42.2% fiber by volume. This was lower than the values for CT-9 and indicated that bleed-out of resin was still inadequate with vacuum and 300 psi pressure in the mandrel.

On Tubes CT-22 and -23 the cure cycle was changed slightly, but no appreciable improvement was evident. The mandrel was pressurized at 50 psi at a mold temperature of 100°F with no vacuum. When the mold temperature reached 150°F the vacuum was applied to the mold cavity and pressure was increased in 50 psi increments at 5°F temperature intervals until 300 psi was reached at 170°F. The mold was then held at 180°F for one hour followed by two hours at 300°F with the pressure maintained at 300 psi. The wall thickness of all these tubes was in the range of 0.040 to 0.050 inch or 0.010 to 0.012 inch/ply. The outside diameter of all tubes which achieved full expansion in the mold was approximately 1.1 inches.

Although the tubes described above were fabricated as part of the process development phase of this work and had received a shortened cure, thirteen of them were subsequently judged to be acceptable for use as test specimens.

As mentioned previously, this first tube mold tool provides a cavity sufficient to accommodate only a four-ply layup. Also, considerable difficulty is encountered in sealing the ends of the pressure bag because of the wrinkling of the rubber tube when folded inside the inner sleeve. New inner sleeve, end caps and tie rod were designed to eliminate these problems and permit the fabrication of the thicker tubes required in the test program. The new mold pieces were designed for use with the same outer mold sleeve. Silicone rubber tubing 1/2-inch I.D. × 1/32-inch wall thickness was ordered for use with this tooling which is designated as Tube Cure Mold #2. Drawings of this tube mold are included in Appendix IV and are assigned numbers 03-2776-01-9 and -11. A photograph of Tube Cure Mold #2 is shown in Figure 11. The major change in the design of this mold is the manner in which the inner sleeve and silicone rubber tubing seal against the end pieces. The inner sleeve is tapered on its outer surface at each end and the rubber tubing is not folded inside the sleeve, but is clamped between the sleeve and the end pieces.

b. Tube Fabrication

A total of 61 graphite/epoxy tubes, including the process development tubes described above, were fabricated during this program. These are listed in Table X. One change was made in the layup procedure starting with Tube CT-37. It was decided that resin bleed-out was still not adequate and that the bleeder plies being between the layup and the expandable mandrel might be contributing to the poor bleed-out. The layup for CT-37 and all later tubes was therefore changed and the graphite/epoxy prepreg was wrapped on the mandrel first. This was covered with a layer of separator cloth (TX-1040), then the 120 glass bleeder cloth and a final wrap of separator cloth. A layer of separator cloth was used between the expandable mandrel and the prepreg for CT-37, but this was eliminated in later tubes since the silicone rubber does not adhere to the cured tube. This procedure resulted in sufficient bleed-out to obtain the desired higher fiber volume tubes.

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*This tube was submitted to AFML but was incorrectly identified as CT-19.

TABLE X

TUBE FABRICATION

Tube No.	Fiber Orientation	No. of Plies	Average Wall Thickness	Outside Diameter	Cure Conditions*	Comments
CT-1	$[0]_T$	2	0.0449	1.073	1	
CT-2	$[0]_T$	4	0.0503	1.086	1	
CT-3	$[0]_T$	3	0.0441	1.065	1	
CT-4	$[0]_T$	4	0.0424	1.095	2	Used Mylar in Place of Separator
CT-5	$[0]_T$	4	0.0331	1.014	2	
CT-6	$[0]_T$	2	0.0201	-	2	
CT-7	$[0]_T$	4	0.0591	1.068	3	A (Acceptable) - S (Used for Specimen)
CT-8	$[0]_T$	4	0.0529	1.100	3	A - N (Not Used for Specimen)
CT-9	$[0]_T$	4	0.0431	1.107	3	A - S
CT-10	$[0]_T$	4	0.0471	1.110	4	
CT-11	$[0]_T$	4	0.0565	1.098	4	
CT-12	$[0]_T$	4	0.0514	1.096	4	
CT-13	$[0]_T$	4	0.0493	1.095	4	
CT-14	$[0]_T$	4	0.0456	1.106	4	A - S
CT-15	$[0]_T$	4	0.0472	1.104	4	A - S
CT-16	$[0]_T$	4	-	-	4	A - S
CT-17	$[0]_T$	4	0.0490	1.003	4	Lost Pressure at 280°F A - S
CT-18	$[0/90]_S$	4	-	-	4	Lost Pressure at 175°F
CT-19	$[0]_T$	4	0.0478	1.102	5	A - N
CT-20	$[0]_T$	4	0.0346	1.102	5	A - N
CT-21	$[0]_T$	4	0.0470	1.108	5	
CT-22	$[0]_T$	4	0.0470	1.108	5	A - N
CT-23	$[0]_T$	4	0.0490	1.106	5	
CT-24	$[0]_T$	4	0.0561	1.098	5	
CT-25	$[0]_T$	4	-	-	6	
CT-26	$[0]_T$	4	0.0528	1.104	6	
CT-27	$[0]_T$	4	0.0495	1.108	7	Lost Pressure at 195°F
CT-28	$[0]_T$	4	-	-	7	
CT-29	$[0]_T$	8	-	-	8	
CT-30	$[0]_T$	4	-	-	9	No Expansion
CT-31	$[0]_T$	4	-	-	10	
CT-32	$[0]_T$	4	-	-	8	Lost Pressure at 300°F
CT-33	$[0]_T$	4	0.0525	1.106	8	
CT-34	$[0]_T$	4	0.0470	1.106	8	A - N
CT-35	$[0]_T$	4	0.0536	1.110	8	A - N
CT-36	$[0]_T$	8	0.1059	1.107	8	A - N
CT-37	$[0]_T$	8	0.1008	1.094	11	A - S
CT-38	$[0]_T$	8	0.0854	1.085	11	A - S
CT-39	$[0]_T$	8	0.0872	1.080	11	A - S
CT-40	$[0]_T$	4	0.0418	1.082	11	A - N
CT-41	$[0]_T$	8	0.0774	1.070	11	A - S
CT-42	$[0/90_2/0]_T$	4	0.0386	1.090	11	A - S
CT-43	$[0/90_2/0]_T$	4	0.0362	1.090	11	A - S
CT-44	$[0/90_2/0]_{2T}$	8	0.0836	1.084	12	A - S
CT-45	$[0]_T$	4	0.0436	1.072	11	A - S
CT-46	$[0]_T$	8	0.0804	1.089	11	A - S
CT-47	$[0]_T$	4	0.0528	1.047	11	
CT-48	$[0]_T$	4	0.0421	1.073	11	A - S
CT-49	$[0/90_2/0]_T$	4	0.0451	1.085	11	A - S
CT-50	$[0]_T$	4	0.0446	1.085	11	
CT-51	$[0/90_2/0]_{2T}$	8	0.0391	1.093	11	A - S
CT-52	$[0/90_2/0]_T$	4	-	-	11	Lost Pressure
CT-53	$[0/90_2/0]_T$	4	0.0436	1.086	11	Lost Pressure at 300°F A - S
CT-54	$[0/90_2/0]_T$	4	-	-	11	Lost Pressure at 180°F
CT-55	$[0/90_2/0]_T$	4	0.0424	1.095	11	
CT-56	$[0/90_2/0]_{2T}$	8	0	1.085	11	
CT-57	$[0/90_2/0]_T$	4	0.0411	1.092	11	A - S
CT-58	$[0/90_2/0]_{2T}$	8	-	-	11	Lost Pressure at 300°F
CT-59	$[0/90_2/0]_T$	4	0.0425	1.091	11	Lost Pressure at 300°F
CT-60	$[0]_T$	4	0.0495	1.066	11	A - N
CT-61	$[0/90_2/0]_{2T}$	8	-	-	11	Lost Pressure at 300°F

*Cure Conditions

1. Cure Pressure = 100 psi   Temperature = 180°F for 2 hr, 300°F for 4 hr
2. Cure Pressure = 200 psi   Temperature = 180°F for 2 hr, 300°F for 4 hr
3. Cure Pressure = 200 psi   Temperature = 180°F for 1 hr, 300°F for 2 hr
4. Cure Pressure = 300 psi   Temperature = 300°F for 2 hr
5. Cure Pressure = 300 psi   Temperature = 300°F for 2 hr with vacuum in mold cavity
6. Cure Pressure = 200 psi/vacuum   Temperature = 180°F for 1 hr, 300°F for 2 hr
7. Cure Pressure = 200 psi/vacuum   Temperature = 180°F for 2 hr, 300°F for 3 hr
8. Cure Pressure = 200 psi/vacuum   Temperature = 180°F for 2 hr, 300°F for 1 hr + 3 hr at 0 psi
9. Cure Pressure = 50 psi/vacuum   Temperature = 180°F for 2 hr, 300°F for 1 hr + 3 hr at 0 psi
10. Cure Pressure = 100 psi/vacuum   Temperature = 180°F for 2 hr, 300°F for 1 hr + 3 hr at 0 psi
11. Cure Pressure = 200 psi/vacuum   Temperature = 180°F for 2 hr, 300°F for 4 hr - Bleeder on Outside of Layup
12. Bleeder on Outside of Layup - Cure Pressure = 200 psi/vacuum   Temperature = 180°F for 2 hr, 300°F for 2 hr + 2 hr at 0 psi

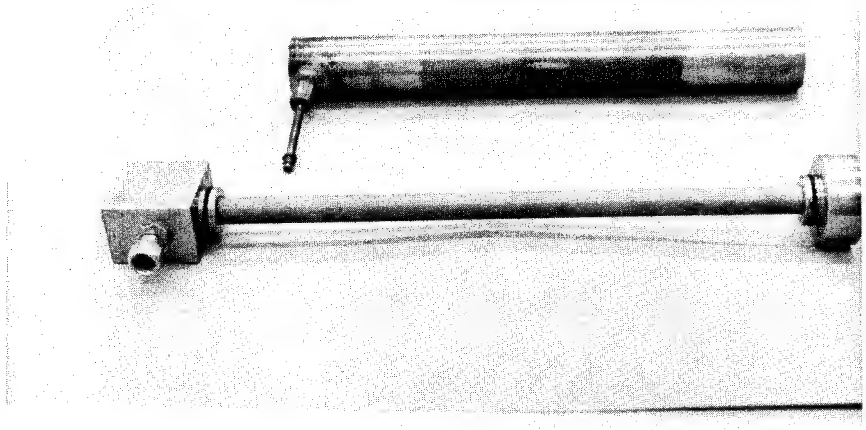


FIGURE 11. TUBE CURE MOLD NO. 2

Figure 12 shows pictorially pertinent information on tube processing. A and B show the tooling used in the manufacture of the tubes. B and C show the curing process and equipment. D shows some of the glossy surface 45% fiber volume tubes with little or no resin bleed-out (inside only), whereas E and F show some of the 55% fiber volume satin surface ones with inside and outside bleed. G shows the automatic ultrasonic scan set-up for tube non-destructive inspection which was developed toward the end of the program.

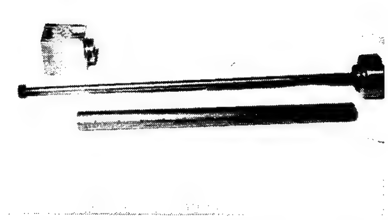
c. Quality Control

Quality control on composite tubes was limited to visual inspection and measurement of dimensions as removed from the mold. The ends of the tube were then trimmed 1/4 inch or more and wall thickness was again measured at four points 90° apart at each end. Another 1/4 inch piece was cut from each end for specific gravity/ fiber content determinations. The eight measurements of wall thickness taken after cutting the ends of the tube were averaged and this average is reported as the nominal wall thickness in Table VII. Three measurements of the tube outside diameter, one at each end and one at the center, were averaged and these are reported as nominal O.D. in the table. Specific gravity and fiber content determinations were made only on tubes which were judged to be acceptable and submitted for fabrication into test specimens.

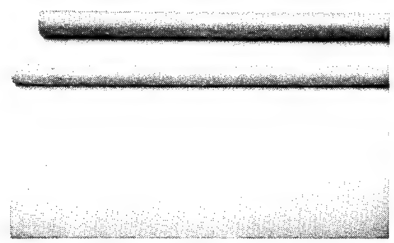
The ultrasonic inspection facility was modified to provide the capability for inspection of the tubes. For tube inspection the sending and receiving transducers were mounted side-by-side with the centerline of the transducers intersecting at the center of the tube. A corner reflector made of aluminum was placed inside the tube to reflect the signal from the sender to the receiver. The transducers then scanned from end to end of the tube, the tube then rotated a step, and the transducers scanned back to the starting end. The tube was rotated a step on each scan until it had been rotated through a full 360° revolution. Only a few tubes were inspected in the ultrasonic facility before the end of the program and these were developmental.

d. Specimen Fabrication

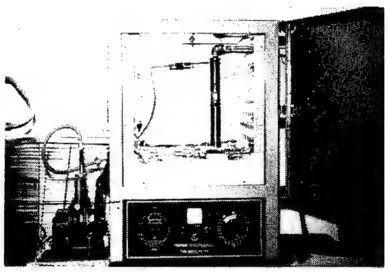
Two types of load introduction tabs for the tube specimens were investigated. The first of these was a solid wrap of NARMCO 551-1581 glass fabric prepreg. Two tubes were prepared for test with this type of load tab, CT-9 and CT-45. The tube was first cut to a length of 10 inches. A three-inch length at each end of the tubes was



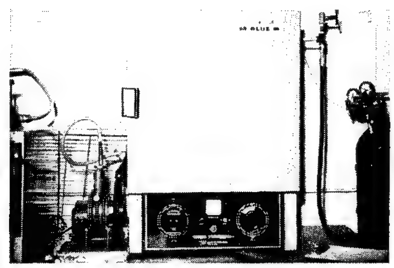
A. 8-Ply Tube Tooling (less female mold)



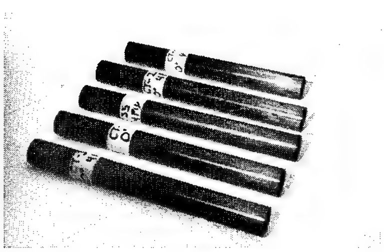
B. 4- and 8-Ply Male Mandrels with Silicone Rubber Pressure Bag in Place



C. Tube Cure Set-up in Oven

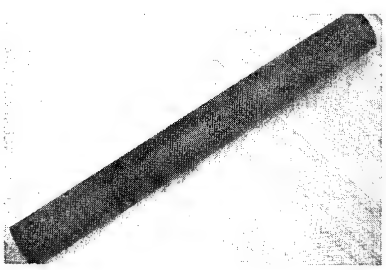


D. Blue M Tube Curing Oven

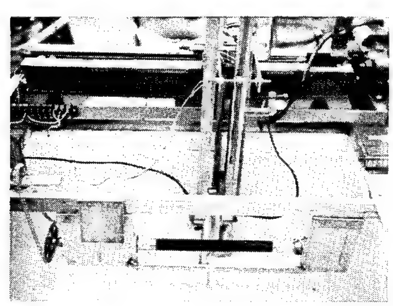


E. Seamless Composite Tubing with Inside Bleed

F. Seamless Composite Tubing with Outside Bleed



G. Outside Bleed Seamless Tubing



H. Ultrasonic Inspection Set-up for Tubes

FIGURE 12. TUBE PROCESSING DETAILS

sanded, primed, and covered with Metlbond 227 adhesive. Strips of prepreg were cut three inches wide and hand wrapped on each end of the tube until a 3/4-inch thick tab had been built up. The section of the tube between was covered with separator cloth which was held in place with Mylar adhesive coated tape. This section was then wrapped with bleeder cloth to the same thickness as the end tabs. The entire layup was then wrapped in a layer of separator cloth and a layer of vent cloth. The entire layup was then sealed in a Mylar vacuum bag with a vacuum connection at one end. This was placed in the air circulating oven and the vacuum connection attached to a vacuum pump. The layup was then cured for one hour at 250°F.

After cure, the ends of the tabs were machined flat and parallel and holes were drilled and tapped in the glass fabric/epoxy tab for attachment to the biaxial test machine. Subsequently, the ends of the tabs adjacent to the test section were machined to a 45° taper. Tubes which had not previously been subjected to a full cure cycle (process development tubes) were then given a post cure at 300°F for an appropriate period depending on its original cure time and the tab cure time.

This method of forming load tabs was not acceptable since the tabs were not round, contained void areas where the layers were not bonded adequately and test results were low (see Section III). It also requires an excessive amount of time to hand wrap the prepreg required for such a thick section. An automatic wrapping machine using 3-inch wide prepreg tape might eliminate these problems, but such a system could not be developed within the scope of this program.

The second method of load tab attachment used only three plies of the glass fabric/epoxy prepreg bonded to the tube with Metlbond 227. These were wrapped on the tube as described above and co-cured at 250°F for one hour in a vacuum bag. A 1/8-inch wide cut in the prepreg was made longitudinally at three points around the circumference of the tube (approximately 120° apart). The cured glass/epoxy laminate was then machined to an exact diameter. A metal load tab was then machined from a 2-1/2 inch O.D. X 1-inch I.D. steel tube. The end of the tab adjacent to the test section was machined to a 45° or 30° bevel depending on the type of test for which the specimen was to be used. The inside diameter of the steel tabs was bored or reamed to match the outside diameter of the machined glass/epoxy laminate on the tube. The steel tab was then cut into three sectors of 120° longitudinally. The steel tabs were then bonded to the glass/epoxy laminate with Metlbond 227 adhesive. Each end was assembled and cured separately at 250°F for one hour. Tubes which had not previously received a full cure were then post cured at 300°F for two hours. The ends of the metal tabs were then machined flat and parallel and holes were drilled and tapped for attachment to the biaxial test machine. This method was used on Tubes CT-14 and CT-16. Later tubes had the metal tabs bonded directly to the tube without the three-ply glass/epoxy intermediate material, using the AF-126-2 adhesive. Pertinent data on all tubes fabricated into specimens are listed in Table XI.

TABLE XI

TUBE TEST SPECIMENS

Tube No.	Fiber Content Volume %	Void Volume %	Density lb/cu. in.	Comments
CT-7	42.34	0.65	0.0524	Metal Load Tabs
CT-9	47.93	0.41	0.0536	Laminated Glass Reinforced Tabs
CT-14	54.96	0.35	0.0550	Metal Tabs on 3-Ply Glass Reinforced Transition
CT-15	47.51	0.44	0.0536	Metal Tabs
CT-16	47.81	0.45	0.0533	Metal Tabs on 3-Ply Glass Reinforced Transition
CT-17	45.55	1.95	0.0523	Metal Tabs
CT-37	50.70	0.78	0.0540	Metal Tabs
CT-38	52.65	0.50	0.0545	Metal Tabs
CT-39	52.00	0.78	0.0542	Metal Tabs
CT-41	55.01	0.72	0.0549	Metal Tabs
CT-42	51.09	0.99	0.0540	Metal Tabs
CT-43	51.02	1.13	0.0538	Metal Tabs
CT-44	53.22	2.15	0.0537	Metal Tabs
CT-45	56.22	0.77	0.0551	Laminated Glass Reinforced Tabs
CT-46	53.78	0.74	0.0546	Metal Tabs
CT-48	50.92	0.58	0.0540	Metal Tabs
CT-49	46.16	2.30	0.0522	Metal Tabs
CT-51	53.52	0.68	0.0546	Metal Tabs
CT-53	47.60	0.54	0.0535	Metal Tabs
CT-57	49.92	1.14	0.0536	Metal Tabs
CT-59	53.20	1.52	0.0539	Metal Tabs

SECTION III

MATERIALS EXPERIMENTAL CHARACTERIZATION

1. GENERAL

This section deals with micromechanical and macromechanical analysis of the flat panel and tube static test data. The micromechanical unidirectional data analysis is given in subsection 2 and the macromechanical $[0/90]_c$ and $[90/0]_c$ data is presented in subsection 3. Summaries of all flat panel static test results are shown in Table XII for tension and Table XIII for compression. Statistical analysis and design allowables development of the normalized data are presented in Section 4 whereas Section 5 presents the analysis of the experimental data on tubes. Detailed specimen data is presented in Appendix II.

2. MICROMECHANICAL ANALYSIS OF UNDIRECTIONAL FLAT PANEL DATA

The unidirectional data were analyzed by grouping it according to orientation for both tension and compression loading. Next, prediction equations for each of the pertinent parameters were developed, then modified, to allow the experimental data to be normalized to a constant fiber volume and void content. A 60% fiber content and 1% void content was selected as realistic baseline values to which the data were normalized. Finally, the normalized experimental data were statistically analyzed to determine average, standard deviation, and confidence limits.

Tables XIV and XV show the raw experimental tension and compression data summaries grouped according to orientation with the $[0]_c$ laminates being used for longitudinal properties and the $[90]_c$ ones for transverse properties.

The method used for predicting longitudinal tensile properties was originally proposed by Tsai(1) based on the "rule of mixtures" technique. The "k" (and k') factor used by Tsai was called a fiber misalignment factor. Here it shall be called the "Void Factor" and is based on an empirically developed mathematical form of the laminate decimal void volume (Vv). The longitudinal modulus is given by the expression

$$E_{\ell L T} = kE_f[1 - K_0(- V_f)] = E_{\ell L C} \tag{1}$$

where

$$k = 1 - (V_v)^2$$

$$K_0 = 1 - \frac{E_m}{Ef}$$

E_m and E_f refer to the longitudinal moduli of the matrix and fiber, respectively. The properties assumed for these predictions are given in Table XVI for both fiber and matrix materials. Included also are the sources used for these values.

Similarly, the longitudinal strengths, $F_{\ell L T}$ or $F_{\ell L C}$, were predicted from the expression

$$F_{\ell L T} = k'F_f[1 - K'_0(1 - V_f)] = F_{\ell L C}* \tag{2}$$

where

$$k' = 0.80\,(1 - Vv) \text{ for ten.}, \quad k' = 0.65\,(1 - Vv) \text{ for comp.}$$

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*Used for prediction of short column ultimate compressive strength as opposed to the significant damage (microbuckling onset) stresses predicted later.

TABLE XII

FLAT SPECIMEN STATIC TENSION DATA SUMMARY

Panel No.	Specimen Nos.	Density lbs/in.^{3}	% Fiber Vol.	% Void Vol.	Lamination Code	Ply Thick., in.	Proportional Limit Stress, ksi @ Long. Strain	Proportional Limit Stress, ksi @ Transv. Strain	Poisson's Ratio	Primary Modulus of Elasticity, 10^6 psi	Ultimate Strength, ksi	Type Failure(2)	Instru-mentation(1)	Nom. Spec. Width, in.	Comments
								- [0] and [90] Laminate Data -							
C-24	4-3A,B	0.0570	65.40	3.57	$[0]_{4T}$	0.00800	-	-	-	28.71	164.3	A,B,C	2	1.00	Strength scatter very large
C-47	5-3A,B,C	0.0573	64.80	2.88	$[0]_{3T}$	0.00844	-	-	-	23.34	177.9	B,C	2	0.50	Strength scatter very large
C-50	5-7A,B,C	0.0563	61.21	3.35	$[90]_{12T}$	0.00858	-	-	0.0215	1.353	4.923		2	0.50	
C-61	61-A,B,C	0.0546	53.97	0.71	$[90]_{12T}$	0.00991	-	-	0.0248	1.10	4.36		2	0.75	
C-68	68-A,B,C	0.0551	56.39	0.82	$[90]_{12T}$	0.00946	-	-	0.0200	1.29	5.62		2	0.75	
								- [0/90] and [90/0] Laminate Data -							
C-26	4-7A,B	0.0575	67.20	3.39	$[0/90]_S$	0.00800	-	N.T.G.*	N.T.G.*	15.48	96.3		1	1.00	
C-63	63-A,D,G,K,N	0.0560	58.77	0.02	$[0/90]_S$	0.00875	-	48.16	0.0479	12.42	77.66		2	0.75	
C-63	63-E,J	0.0560	58.77	0.02	$[0/90]_S$	0.00875	-	40.10	0.0600	12.63	73.99		2	~~1.00~~ 0.75	
C-64	64-B,E,H,L,P	0.0559	58.37	0	$[0/90]_S$	0.00910	-	58.68	0.0412	12.10	87.43		2	0.75	
C-27	4-9A,B	0.0570	64.00	3.22	$[90/0]_S$	0.00800	-	N.T.G.*	N.T.G.*	13.73	69.74		1	1.00	
C-39	5-11B,C	0.0559	59.70	3.34	$[90/0]_S$	0.00742	-	33.00	0.0232	14.40	97.22		2	1.00	
C-39	5-11A	0.0559	59.70	3.34	$[90/0]_S$	0.00742	-	N.T.G.*	N.T.G.*	16.30	45.23		2	1.00	Strain rate 10 times higher than spec.
C-48	5-11G,H,J	0.0560	55.45	1.56	$[90/0]_S$	0.00825	-	N.T.G.*	N.T.G.*	13.643	38.26		2	1.00	Q.C. tests low
C-57	C-57Z†	0.0551	56.61	0.92	$[0/90_2/0]_{3T}$	0.00880	30.983	N.T.G.*	N.T.G.*	11.085	67.682		2	0.50	
C-57	T-57J,K,L	0.0551	56.61	0.92	$[0/90_2/0]_{3T}$	0.00880	-	52.600	0.0771	12.074	68.996		2	0.75	
C-60‡	60-B,E,H,L,P	0.0542	51.66	0.68	$[0/90_2/0]_{3T}$	0.00972	-	40.525	0.0314	10.535	72.795		2	0.75	
C-67‡	67-K,N,R	0.0552	56.34	0.68	$[0/90_2/0]_{3T}$	0.00972	-	-	-	12.403	62.640		1	0.50	Baldwin direct reading/extensometer
C-67	67-K,N,R	0.0552	56.34	0.63	$[0/90_2/0]_{3T}$	0.00860	-	-	0.0301	12.733	63.879		2	0.50	L.C./S.G.

Note: Specimens tested in accordance with SwRI 03-401 unless noted

*N.T.G. - no transverse gage

†Gage comparison specimen for correction of compression specimen modulus

‡Comparison of Baldwin direct read./extens. data with that of load cell/strain gage

(1) Instrumentation
1 - Baldwin direct reading load with autographic extensometer
2 - Load cell/specimen strain gage with automatic digital readout

(2) Failure Types
A - Delamination
B - Net section tension
C - Longitudinal splitting
D - Compression diagonal shear
E - Compression instability on unsupported edge

TABLE XIII

FLAT SPECIMEN STATIC COMPRESSION DATA SUMMARY (Ref. SwRI Dwg. 03-2776-01-3 on UT/C Specimen)

Panel No.	Specimen Nos.	Density lbs/in.^{3}	% Fiber Volume	% Void Volume	Lamination Code	Ply Thick., in.	Proportional Limit Stress ksi	Primary Modulus of Elast., * 10^6 psi	Ultimate Strength, ksi	Type Failure(1)	Instru-mentation†	Comments
					- $[0]$ and $[90]$ Laminate Data -							
C-49	5-5-B, C	0.0564	61.87	3.39	$[0]_{12T}$	0.00830	-	23.849	133.000		2	
C-53	4-11-A, B	0.0546	51.90	2.67	$[0]_{12T}$	0.00911	-	19.642	91.120		1	
C-69	69-A	0.0553	56.88	0	$[0]_{18T}$	0.00920	-	21.364	71.428		2	Ends not flat and parallel within tol.
C-69	69-B, C, D, E	0.0553	56.88	0	$[0]_{18T}$	0.00920	-	20.328	97.867	E, C	2	
C-54	4-13-A, B	0.0554	56.20	2.89	$[90]_{12T}$	0.00870	10.340	1.646	19.620		1	
C-68	68-D, E, F	0.0551	56.39	0.82	$[90]_{12T}$	0.00946	16.80	1.210	26.83	D	2	
					- $[0/90]$ and $[90/0]$ Laminate Data -							
C-40	5-13-A, C, E	0.0552	55.71	3.04	$[0/90_2/0]_{3T}$	0.00810	-	10.682	76.490		2	
C-45	4-15-A, B	0.0546	49.40	1.74	$[0/90_2/0]_{3T}$	0.00850	19.55	9.232	29.590		1	Q.C. tests low
C-57	57-C, U, DD	0.0551	56.61	0.92	$[0/90_2/0]_{3T}$	0.00880	-	9.963	80.250	D	2	
C-55	4-17-A, B	0.0554	56.95	3.16	$[90/0_2/90]_{3T}$	0.00832	33.15	12.041	62.190		1	

*Correction factor of 1.09 has been applied to experimental data to give result shown.

†1 - Baldwin direct reading/compressometer autographic measurement.
2 - Baldwin direct reading/strain gage measurement

(1) Types of Failure
A - Delamination
B - Net section tension
C - Longitudinal splitting
D - Compression diagonal shear
E - Instability of unsupported edge

TABLE XIV

$[0]_c$ AND $[90]_c$ STATIC TENSION DATA SUMMARY ON FLAT SPECIMENS

Panel No.	Specimen No.	Density lbs/in.^{3}	Fiber Volume %	Void Volume %	Laminate Code	Actual Poisson's Ratio	Calculated Poisson's Ratio	Actual Primary Modulus of Elast. E_p 10^6psi	Calc. Primary Modulus of Elast. E_ℓ 10^6psi	Actual Ultimate Strength σ_u ksi	Calc. Ultimate Strength Ftu ksi	$\frac{E_p}{E_\ell} \times 100$ %	$\frac{\sigma_u}{F_{tu}} \times 100$ %
Longitudinal													
C-24	4-3A	0.0570	65.4	3.57	$[0]_{4T}$	-	0.133	31.16	25.65	148.6	205.0	121	72.5
	4-3B	0.0570	65.4	3.57	$[0]_{4T}$	-	0.133	26.26	25.65	180.0	205.0	102	87.7
C-47	5-3A	0.0573	64.8	2.88	$[0]_{3T}$	-	0.130	24.03	25.44	206.8	205.0	93.5	100.5
	5-3B	0.0573	64.8	2.88	$[0]_{3T}$	-	0.130	24.05	25.44	191.8	205.0	93.5	93.5
	5-3C	0.0573	64.8	2.88	$[0]_{3T}$	-	0.130	21.93	25.44	135.0	205.0	84.7	65.8
Transverse													
C-50	5-7A	0.0563	61.21	3.35	$[90]_{12T}$	0.0223		1.40	1.69	5.17	4.056	82.8	127.5
	5-7B	0.0563	61.21	3.35	$[90]_{12T}$	0.019		1.28	1.69	5.34	4.056	75.7	131.7
	5-7C	0.0563	61.21	3.35	$[90]_{12T}$	0.0231		1.38	1.69	4.26	4.056	81.7	105.0
C-61	61A	0.0546	53.97	0.71	$[90]_{12T}$	0.0270		1.12	1.75	4.36	5.980	64.0	72.9
	61B	0.0546	53.97	0.71	$[90]_{12T}$	0.0225		1.08	1.75	5.10	5.980	61.7	85.3
	61C	0.0546	53.97	0.71	$[90]_{12T}$	-		-	1.75	5.20	5.980	-	-
C-68	68A	0.0551	56.39	0.82	$[90]_{12T}$	0.0210		1.31	1.75	5.75	5.739	74.9	100.2
	68B	0.0551	56.39	0.82	$[90]_{12T}$	0.0200		1.34	1.75	5.08	5.739	76.6	88.5
	68C	0.0551	56.39	0.82	$[90]_{12T}$	0.0190		1.22	1.75	6.02	5.739	69.7	104.9

TABLE XV

$[0]_c$ AND $[90]_c$ STATIC COMPRESSION DATA SUMMARY ON FLAT SPECIMENS

Panel No.	Specimen No.	Density lbs/in.^{3}	Fiber Volume %	Void Volume %	Laminate Code	No. of Plies	Load Orientation	Actual Primary Modulus of Elast. E_p, 10^6psi	Calc. Primary Modulus of Elast. E_ℓ, 10^6psi	Actual Ultimate Strength σ_U, ksi	Calc. Ultimate Strength F_{tU}, ksi	$\frac{E_p}{E_\ell} \times 100$ %	$\frac{\sigma_U}{F_{tU}} \times 100$ %
Longitudinal													
C-49	5-5B	0.0564	.6187	.0339	$[0]_{12T}$	12	0^o	23.2	24.31	131.5	134.2	95.4	98.0
	5-5C	0.0564	.6187	.0339	$[0]_{12T}$	12	0^o	24.45	24.31	134.5	134.2	100.6	100.2
C-53	4-11A	.0546	.519	.0267	$[0]_{12T}$	12	0^o	19.02	20.49	88.12	113.9	92.8	78.0
	4-11B	.0546	.519	.0267	$[0]_{12T}$	12	0^o	20.23	20.49	94.12	113.9	98.7	83.3
C-69	69A	0.0553	.56877	0	$[0]_{18T}$	18	0^o	21.35		71.43			
	69B	0.0553	.56877	0	$[0]_{18T}$	18	0^o	20.80		97.70			
	69C	0.0553	.56877	0	$[0]_{18T}$	18	0^o	21.30		100.69			
	69D	0.0553	.56877	0	$[0]_{18T}$	18	0^o	19.53		95.01			
	69E	0.0553	.56877	0	$[0]_{18T}$	18	0^o	19.70		98.06			
Transverse													
C-54	4-13A	.0554	.562	.0289	$[90]_{12T}$	12	0^o	1.96	1.67	22.72	25.49	117.4	89.1
	4-13B	.0554	.562	.0289	$[90]_{12T}$	12	0^o	1.33	1.67	16.51	25.49	79.6	64.8
C-68	68D	.0551	.5639	.0082	$[90]_{12T}$	12	0^o	1.287	1.75	26.67	29.81	73.5	89.5
	68E	.0551	.5639	.0082	$[90]_{12T}$	12	0^o	1.112	1.75	26.21	29.81	63.5	87.9
	68F	.0551	.5639	.0082	$[90]_{12T}$	12	0^o	1.22	1.75	27.61	29.81	69.7	92.6

TABLE XVI

CONSTITUENT MATERIAL PROPERTIES

Property	Value	Reference
Fiber: Courtauld's HTS		
F_{fTU}	400,000 Psi	Hercules
E_{fL}	39 x 10^6 Psi	Hercules
E_{fT}	2.0 x 10^6 Psi	Assumption (Ref 2)
ν_{fL}	0.30	Assumption
G_f	16.25 x 10^6	Calculated
ν_{fT}	0.0154	Calculated
Matrix: ERL 2256		
F_{mTU}	14,000 Psi	Union Carbide
F_{mCU}	29,000 Psi	Ref 3
E_{mL}, E_{mT}	0.545 x 10^6 Psi	Union Carbide
$\nu_{mL} = \nu_{mT}$	0.36	Union Carbide
G_m	0.20 x 10^6 Psi	Union Carbide

TABLE XVII

LONGITUDINAL TENSILE EXPERIMENTAL/ CALCULATED PROPERTIES COMPARISON

Panel No.	Fiber Volume	Void Volume	$F_{\ell TU}$(ksi) Exp	$F_{\ell TU}$(ksi) Calc	$E_{\ell LT}$x10^6 psi Exp	$E_{\ell LT}$x10^6 psi Calc
C-24	.654	.0357	164.3	205	28.71	25.66
C-47	.648	.0288	199.3	205	23.34	25.44

$$K_0' = 1 - \frac{F_{mTU}}{F_{fTU}} \text{ for ten.},$$

$$K_0' = 1 - \frac{F_{mCU}}{F_{fCU}} \text{ for comp.}$$

The longitudinal Poisson's ratio calculation utilized equation (5-7), page 77 of Ref (4) and was expressed as

$$\nu_{\ell LT} = \nu_{fLT} V_f + \nu_m V_m \qquad (3)$$

Properties calculated from these expressions correlated reasonably well with the experimental data, as can be seen from Table XVII. The $F_{\ell LT}$ of Panel C-24 specimens was suspect because of low quality control test results* indicating possible fiber breakage or other damage prior to test.

The transverse tensile properties were not so easily predicted. The approach used was based on expressions given on page 77 of Ref (4) with justification presented by Whitney [(2)] to include anisotropic filaments. Whitney's findings indicated that the transverse modulus (E_T) can be determined from existing analyses if the transverse stiffness (E_{fTT}) of the filament is known. Whitney also stated "the implied transverse stiffness of the filaments should be on the order of 2×10^6 psi."

The expression for the laminate transverse modulus then becomes,

$$E_{TT} = E_m \left[\frac{1 + \delta \eta V_f}{1 - \eta V_f} \right] \qquad (4)$$

where

$\delta = 2$, a measure of the reinforcement which depends on boundary conditions

$$\eta = \left(\frac{E_f}{E_m} - 1 \right) \Big/ \left(\frac{E_f}{E_m} + \delta \right)$$

The transverse tensile failure stress was predicted from an expression given by Chamis, [(5)]

$$S_{TT} = \beta_{22T} \frac{\epsilon_{mpt}}{\beta_\nu \phi_{\mu 22}} E_{\ell TT} \qquad (5)$$

*See Section II

β_{22T} is the theory-experiment correlation factor. Chamis gave a value of 0.70 for the Morganite II Graphite/Epoxy system. It was used in this report because of the similarities betweeen that system and the Courtauld's HTS/Epoxy system used herein. ϵ_{mpt} is the allowable matrix tensile strain. A value of 0.11 in./in. was used. β_v is the void effect and was determined by:

$$\beta_v = \frac{1}{\left[1 - \frac{4V_v}{\pi V_m}\right]}$$

where

V_m = matrix volume

V_v = void volume

$\phi_{\mu_{22}}$ is the matrix strain magnification factor. It is a function of fiber volume, fiber and matrix Poisson's Ratios, fiber and matrix moduli, and applied stresses. It is determined from the following expression:

$$\phi_{\mu_{22}} = \left[\frac{1}{1 + p(A-1)}\right]\left[1 + p\,(\nu_{fLT} - \nu_{mLT}\bar{A})\left(\frac{E_{TT}\sigma_L - \nu_{21}E_{LT}\sigma_T}{E_{LT}\sigma_T - \nu_{12}E_{TT}\sigma L}\right)\right] \tag{6}$$

In this expression σ represents applied stress. Since only transverse stresses were applied, $\sigma_L = 0$ and the expression becomes,

$$\phi_{\mu_{22}} = \left[\frac{1}{1 + p(\bar{A}-1)}\right][1 + p(\nu_{fLT} - \nu_{mLT}\bar{A})(-\nu_{21})] \tag{7}$$

where

$$p = \left(\frac{4Vf}{\pi}\right)^{1/2}$$

$$A = \left[\frac{1 - \nu_{fLT}\nu_{fTT}}{1 - \nu_{mLT}\nu_{mTT}}\right]\left(\frac{E_{mTT}}{E_{fTT}}\right)$$

A summary of the average experimental and calculated values for each panel is shown in Table XVIII. As can be seen from the table, the experimental data and calculated properties correlate reasonably well. The longitudinal and transverse compression modulus predictions utilized the same expressions as their respective tensile modulus expressions (Eq. 1 and 4). Longitudinal compressive failure stress (as measured on the platen supported jig used herein) was predicted from the following:

TABLE XVIII

TRANSVERSE TENSILE EXPERIMENTAL/
CALCULATED PROPERTIES COMPARISON

Panel No.	Fiber Volume	Void Volume	$F_{\ell TT}$ Exp	$F_{\ell TT}$ Calc	$E_{\ell TT}$ Exp	$E_{\ell TT}$ Calc
C-50	.6120	.0335	4920	4296	1.35	1.21
C-61	.5397	.0071	4890	5741	1.10	1.10
C-68	.5639	.0082	5620	5644	1.29	1.14

$$S_{\ell LC} = F_{mcu}\left[\beta_{mc}V_m + \beta_{fc}V_f\left(\frac{E_{fL}}{E^*_{mL}}\right)\right] \tag{8}$$

F_{mcu} is the matrix compressive strength and is given in Table XIV. β_{mc} is the matrix theory-experiment correlation factor and was reported by Chamis to be 1.00 for the Morganite II system. β_{fc} is the fiber theory-experiment correlation factor assumed to equal 0.15 for this report. The value predicted here (and measured experimentally) is believed to be the stress (strain) at which 0° ply fiber microbuckling starts based on the observations of Section IV. 2.

The transverse compressive strength of the unidirectional laminate ($S_{\ell TC}$) was computed from an expression very similar to the transverse tensile strength form:

$$S_{\ell TC} = \frac{\beta_{22c}\epsilon_{mpc}E_{\ell T}}{\beta_v \phi_{\mu 22}} \tag{9}$$

β_{22c} being the theory-experiment correlation factor (1.47 for this report) and ϵ_{mpc} being the limiting failure compressive strain. This value was assumed to be 0.040 in./in. This strain occurred midway between the proportional limit and the "knee" in the matrix stress strain curve.* It was assumed that this was the point at which local instability would occur.

The other components of equation (9) are identical to equation (5).

TABLE XIX

UNIDIRECTIONAL COMPRESSIVE EXPERIMENTAL/ CALCULATED DATA COMPARISON

Panel	Fiber Volume	Void Volume	$S_{\ell c} \times 10^3$ psi Exp	$S_{\ell c} \times 10^3$ psi Calc	$E_{\ell c} \times 10^6$ psi Exp	$E_{\ell c} \times 10^6$ psi Calc
Longitudinal						
C-49	.6187	.0339	133.0	125.8	23.83	24.31
C-53	.5190	.0267	91.0†	108.4	19.63	20.49
Transverse						
C-54	.5620	.0289	19.62	22.08	1.65	1.13
C-68	.5639	.0082	26.83	26.62	1.21	1.14

*Reference (3), Chapter on Material Properties.

†LOW quality control test results indicate fiber damage prior to fabrication.

Compressive experimental and calculated data are summarized and compared in Table XIX.

Figure 5-2, page 78 of Ref (4) was used for estimating a shear modulus. This figure assumes a square fiber array pattern of A/B = 1.00. Using this assumption and a fiber volume of 0.4787 the calculated $G_{\ell t}$ was 0.552 × 10^6 psi. A V_f = 0.4787 was determined by taking the average of the fiber volumes for tubes CT-9 (0.4793) and CT-16 (0.4781). These are the only two 0° fiber tubes tested in pure torsion (shear) from which shear modulus data were available.† Experimental results yielded CT-9 shear modulus, $G_{\ell t}$ = 0.646 × 10^6 psi and a CT-16 shear modulus, $G_{\ell t}$ = 0.535 × 10^6 psi. The average of these values is 0.590 × 10^6 psi which compares very favorably with the 0.552 × 10^6 psi calculated value.

The process of developing normalization equations consisted of taking the mechanical properties prediction equations (Equations 1, 2, 4, 5, 8 and 9) and bringing all values to a fiber fraction content of 0.600 and a void fraction of 0.01. These values were typical of this effort's flat panel experimental results and were considered representative of industry fabrication capability for that time period.‡ The process is shown in the following example and the normalization equations used are summarized in Table XX as equations 10 thru 18.

To normalize the longitudinal modulus $E_{\ell LT}$, the following expression was used:

$$\frac{E_{\ell LT_N}}{E_{\ell LT_A}} = \frac{k_N[1 - Ko_N(1 - V_{f_N})]}{k_A[1 - Ko_A(1 - V_{f_A})]}$$

$$E_{\ell LT_N} = E_{\ell LT_A} \frac{k_N[1 - Ko_N(1 - V_{f_N})]}{k_A[1 - Ko_A(1 - V_{f_A})]}$$

$$\text{for } V_{f_N} = 0.60, \quad V_v = 0.01 \tag{19}$$

*Reference (3), Chapter on Material Properties.

†See subsection 5.

‡Late 1970, early 1971.

TABLE XX

SUMMARY OF NORMALIZATION EQUATIONS FOR UNIDIRECTIONAL COMPOSITES
($V_{f_N} = 0.600, \quad V_{v_N} = 0.010$)

Longitudinal Tension

Modulus: $E_{LT_N} = E_{LT_A} \times \left[\frac{E_{LT_{CN}}}{E_{LT_{CA}}}\right]$ (10)

Strength: $S_{LT_N} = S_{LT_A} \times \left[\frac{S_{LT_{CN}}}{S_{LT_{CA}}}\right]$ (11)

Transverse Tension

Modulus: $E_{TT_N} = E_{T_A} \times \left[\frac{E_{LT_{CN}}}{E_{LT_{CA}}}\right]$ (12)

Strength: $S_{TT_N} = S_{TT_A} \times \left[\frac{S_{LT_{CN}}}{S_{LT_{CA}}}\right]$ (13)

Longitudinal Compression

Modulus: $E_{LC_N} = E_{LT_N} \times \left[\frac{E_{LT_{CN}}}{E_{LT_{CA}}}\right]$ (14)

Strength: $S_{LC_N} = S_{LC_A} \times \left[\frac{S_{LT_{CN}}}{S_{LT_{CA}}}\right]$ (15)

Transverse Compression

Modulus: $E_{TC_N} = E_{TT_N} \times \left[\frac{E_{LT_{CN}}}{E_{LT_{CA}}}\right]$ (16)

Strength: $S_{TC_N} = S_{LC_N} \times \left[\frac{S_{LT_{CN}}}{S_{LT_{CA}}}\right]$ (17)

Torsion

$G_{LT_N} = G_{LT_A} \times \left[\frac{G_{LT_{CN}}}{G_{LT_{CA}}}\right]$ (18)

$$E_{\ell LT_N} = E_{\ell LT_A}\left[\frac{(0.6055)}{k_A\,[1 - Ko_A(1 - V_{f_A})]}\right]$$

(19 Cont'd)

The normalized experimental and calculated properties for the unidirectional flat specimens are shown in Tables XXI and XXII. Table XXI presents the tensile data and Table XXII, the compression.

3. MACROMECHANICAL ANALYSIS OF $[0/90]_c$ AND $[90/0]_c$ FLAT PANEL DATA

Macromechanics data analysis consisted of (1) making micromechanics predictions of the lamina mechanical properties for each of the experimental panel fiber and void volume combinations, (2) predicting angleply mechanical properties utilizing the linearly elastic theory for laminated plates[6] and the maximum strain failure theory,[7] (3) developing normalization equations to bring all test data to a common fiber and void content, and (4) comparing angleply test data to that supplied in the theory.

To utilize the macromechanics predictive equations the longitudinal and transverse properties for each panel must be determined. These properties are summarized in Table XXIII. For use in

TABLE XXI

NORMALIZED TENSILE DATA SUMMARY (UNIDIRECTIONAL)
(Normalized to $V_f = 0.60, \quad V_v = 0.01$)

Panel No.	Specimen No.	Normalized Experimental Tensile Strength psi	Calculated Tensile Strength psi	Normalized Experimental Tensile Modulus psi	Calculated Tensile Modulus psi
Longitudinal					
C-24	4-3A	143,300*		28.62×10^6	
	4-3B	170,340		24.12×10^6	
C-47	5-3A	196,010	194,500	22.30×10^6	23.62×10^6
	5-3B	181,800		22.32×10^6	
	5-3C	128,000*		20.35×10^6	
Average		182,720		23.54×10^6	
Standard Deviation		12,860		3.14×10^6	
Transverse					
C-50	5-7A	6,598		1.37×10^6	
	5-7B	6,815		1.26×10^6	
	5-7C	5,437		1.35×10^6	
C-61	61A	4,164		1.25×10^6	
	61B	4,871	5,483	1.21×10^6	1.19×10^6
	61C	4,966		-	
C-68	68A	5,586		1.37×10^6	
	68B	4,935		1.41×10^6	
	68C	5,848		1.28×10^6	
Average		5,469		1.31×10^6	
Standard Deviation		855		0.072×10^6	

*Specimen 4-3A was adjacent to a damaged section of Panel C-24 and could be damaged. Specimen 5-3C fractured in a manner which indicated bending in the specimen. Both specimens were not included in estimates.

TABLE XXII

NORMALIZED COMPRESSION DATA SUMMARY (UNIDIRECTIONAL)
(Normalized to $V_f = 0.60$, $V_v = 0.01$)

Panel No.	Specimen No.	Normalized Experimental Compressive Strength psi	Calculated Compressive Strength psi	Normalized Experimental Compressive Modulus psi	Calculated Compressive Modulus psi
Longitudinal					
C-49	5-5B	128,500		22.54×10^6	
	5-5C	131,400		23.75×10^6	
C-53	4-11A	99,940*	122,947	21.92×10^6	23.62×10^6
	4-11B	106,750*		23.32×10^6	
Average		129,950		22.88×10^6	
Standard Deviation		2,051		$.814 \times 10^6$	
Transverse					
C-54	4-13A	25,856		2.07×10^6	
	4-13B	19,330		1.40×10^6	
C-68	68D	25,906	25,856	1.26×10^6	1.19×10^6
	68E	25,460		1.09×10^6	
	68F	26,820		1.20×10^6	
Average		24,674		1.40×10^6	
Standard Deviation		3,029		0.389×10^6	

*Panel C-53 exhibited low longitudinal flexure Quality Control Test Results. Values were not used in average and standard deviation calculations.

TABLE XXIII

MICROMECHANICS ANALYSIS UNIDIRECTIONAL LAMINA DATA PREDICTION SUMMARY

Panel No.	Fiber Volume	Void Volume	F_ℓ ksi	E_ℓ $\times 10^6$ psi	F_t ksi	E_T $\times 10^6$ psi	ν_{LT}	$\epsilon_{\ell max}$	$\epsilon_{t max}$
Tensile Test Panels									
C-26	.6720	.0339	211.3	26.36	4.12	1.30	.307	.00802	.00317
C-63	.5877	.0002	192.6	23.14	6.52	1.171	.325	.00832	.00557
C-64	.5837	0	191.4	22.99	6.69	1.165	.325	.00833	.00574
C-27	.6400	.0322	202.1	25.13	4.32	1.250	.310	.00804	.00346
C-39	.5970	.0334	189.0	23.48	4.42	1.184	.312	.00805	.00373
C-48	.5545	.0156	177.7	21.95	4.64	1.126	.316	.00809	.00412
C-57	.5661	.0092	184.3	22.31	5.57	1.139	.323	.00826	.00490
C-60	.5166	.0068	166.9	20.49	4.85	1.074	.319	.00814	.00452
C-67	.5634	.0068	183.9	22.21	5.74	1.135	.324	.00828	.00506
Compression Test Panels									
C-40	.5571	.0304	115.1	21.95	21.88	1.126	.316	.00524	.01942
C-57	.5661	.0092	117.0	22.31	26.31	1.139	.323	.00524	.02301

the macromechanics maximum strain theory expressions, the panel maximum strains were determined simply by dividing the ultimate stresses* by the respective moduli*.

*Analytically determined values.

As previously mentioned, the $[0/90]_c$ mechanical properties were estimated using standard laminated plate theory with the stiffness coefficients being estimated utilizing the plane strain assumption. In predicting the proportional limit stresses, the values achieved correlate very closely with the "knee" observed in the longitudinal stress/transverse strain curve obtained from the transverse gages used on the tensile specimens (see Appendix II for examples). Table XXIV compares calculated and experimental modulus, stress, and Poisson's ratio for all of the $[0/90]_c$ static flat panel tests. Both tension and compression results are shown in the table. Panel C-67 stress values asterisk (*) exhibited no knee as experienced by other specimens. Panels C-26, C-27 and C-48 did not have transverse strain data available, therefore, the only value shown is the ultimate failure stress.

The equations developed to normalize all panel test data to the set standard fiber and void content (0.60 and 0.01, respectively) took the following forms:

$$E_n = \left(\frac{E_{cn}}{E_{cex}}\right) E_{ex} \tag{20}$$

$$\sigma_n = \left(\frac{\sigma_{cn}}{\sigma_{cex}}\right) \sigma_{ex} \tag{21}$$

where the subscripts had the following meanings

n – normalized
cn – calculated normalized ($V_f = 0.60$, $V_v = 0.01$)
cex – calculated experimental, using the fiber and void contents measured on the panels
ex – raw, experimental values

Normalized modulus and stress values for all flat panel static tests are given in Table XXV. Also shown are the calculated and raw experimental properties for comparative purposes. A qualitative estimate of the quality control test results is included for reference. Panel C-26 test specimens exhibited a higher than average transverse flexure strength which may account for the slightly higher mechanical properties being recorded. The three $[90/0]_S$ panels (C-27, C-39, C-48) all recorded slightly low Q.C. results. These same panels also showed lower failure strengths than other panels. Examination of Fig. 13, the ultrasonic inspection results for C-39 and C-48 showed further indications of poor panel quality.

The average, normalized tensile modulus for all panels tested was 13.37×10^6 psi with a standard deviation of 1.13×10^6 psi (see Table XXV). All data points were used as low Q.C. results seem to have little, if any, effect on modulus. Panels C-63, C-64, C-39, C-57 and C-60 were used to compute the average normalized proportional limit stress levels. These specimens all had transverse gages functioning and a definite "knee" in the transverse strain curve was observed. This average normalized stress at the knee is 46,050 psi with a standard deviation of 5,010 psi. For ultimate failure strength, the average, normalized values from all panels except C-39 and C-48 were used. These two panels had low Q.C. results which obviously effects ultimate strength even though it doesn't effect the modulus. Average normalized ultimate strength was 74,230 psi with a standard deviation of 8,900 psi. Poisson's ratio values were not normalized. Average and standard deviation experimental values were calculated to be 0.041 and 0.020, respectively.

Calculated normalized proportional limit values were 25% higher than the normalized experimental stresses whereas the calculated normalized ultimate strength values were 31% higher than normalized experimental failure stresses. However, normalized calculated moduli of elasticity values were 93.5% of the average experimental values. While there was much scatter in the measured experimental Poisson's ratio, the average correlated well with the calculated value.

Agreement between experiment and theory for modulus prediction was not as good in the compression test specimens as it was in the tension specimens (predicted values being 11.4% higher than experimental ones). Table XXVI shows a comparison similar to that for the tensile data. Ultimate strength correlates well with the predicted values with the calculated stresses being 96.2% of the experimental ones. Since no transverse strain data were

TABLE XXIV

EXPERIMENTAL/ANALYTICAL MECHANICAL PROPERTIES COMPARISON (0/90 Orientation Except as Noted)

Panel No.	Orientation	Average Experimental Modulus x 10^6 psi	Calculated Modulus x 10^6 psi	Average Experimental Stress, ksi		Calculated Stress, ksi		Average Experimental Poisson's Ratio	Calculated Poisson's Ratio
				Prop. Limit*	Ultimate †	Prop. Limit‡	Ultimate **		
Tension									
C-26	$[0/90]_S$	15.48	13.90	††	96.30	44.00	111.5	-	0.042
C-63	$[0/90]_S$	12.42	12.22	48.16	77.66	68.00	101.7	0.048	0.042
C-64	$[0/90]_S$	12.10	12.14	58.68	87.43	69.76	101.0	0.041	0.042
C-27	$[90/0]_S$	13.73	13.26	††	69.74	46.00	106.5	-	0.042
C-39‡‡	$[90/0]_S$	15.03	12.39	33.00 †	33.00 ***	46.15	99.8	0.023	0.042
C-48	$[90/0]_S$	13.64	11.55	††	38.26***	47.50	93.2	-	0.042
C-57	$[0/90_2/0]_{3T}$	12.07	11.79	52.60	69.00	57.80	97.3	0.077	0.042
C-60	$[0/90_2/0]_{3T}$	10.54	10.80	40.52	72.80	48.81	88.0	0.031	0.042
C-67	$[0/90_2/0]_{3T}$	12.73	11.74	†††	63.88	59.32	97.1	0.030	0.042
Compression									
C-40	$[0/90_2/0]_{3T}$	10.63	11.60	††	76.49	60.79	74.00‡‡‡	-	-
C-57	$[0/90_2/0]_{3T}$	9.97	11.79	††	80.25	61.83	77.00‡‡‡	-	-

*Average experimental stress at which first 90° ply failure occurred was assumed to be at proportional limit (as evidenced by a slope change in the transverse strain).

†Experimental failure stress.

‡ Based on max. strain criterion using 90° lamina failure strain for tension and 0° lamina failure strain for compression (see Table XXIII).

** Based on max. strain criterion using 0° lamina failure strain for tension (see Table XXIII).

††Specimens had no transverse strain data recorded, but longitudinal strain curve was linear to failure.

‡‡Panel C-39 specimens were tested prior to the automatic data acquisition system being implemented. The loading was interrupted at intervals to take gage readings.

***Panels had low Q. C. test results.

†††Specimens exhibited no "knee" in the longitudinal or transverse strain curves and were straight line to failure.

‡‡‡Technique of max. allowable longitudinal ply strain used in tension is not applicable to compression ultimate strength since failure is different, i.e., micromechanics technique used.

TABLE XXV

$[0/90]_c$ NORMALIZED FLAT PANEL DATA SUMMARY (TENSION)

						Experimental Data				Analytical Data				Normalized Data*					
Panel No.	Orientation	No. of Plies	Fiber Volume	Void Volume	Q.C. Test Results	E_{ex} $\times 10^6$psi	σ_{ex}† ksi	$\bar{\sigma}_{ex}$ ksi	ν_{ex}	E_{cex} $\times 10^6$psi	σ_{cex} ksi	$\bar{\sigma}_{cex}$ ksi	ν_{cex}	E_{nex} $\times 10^6$psi	σ_{nex} ksi	$\bar{\sigma}_{nex}$ ksi	σ_{cn} ksi	$\bar{\sigma}_{cn}$ ksi	E_{cn} $\times 10^6$psi
C-26	$[0/90]_S$	4	.6720	.0339	High	15.48	‡	96.30	-	13.90	44.00	111.5	0.042	13.88	-	83.99	57.50	97.25	12.468
C-63	$[0/90]_S$	4	.5877	.0002	Ave	12.42	48.16	77.60	.048	12.22	68.00	101.7		12.47	40.72	74.20			
C-64	$[0/90]_S$	4	.5837	0	Ave	12.10	58.68	87.43	.041	12.14	69.76	101.0		12.43	48.37	84.18			
C-27	$[90/0]_S$	4	.6400	.0322	Low	13.73	‡	69.74	-	13.26	46.00	106.5		12.91	-	63.68			
C-39	$[90/0]_S$	4	.5970	.0334	Low	15.35	33.00	33.00	.023	12.39	46.15	99.8		15.45	41.12	41.12**			
C-48	$[90/0]_S$	4	.5545	.0156	Low	13.64	‡	38.26	-	11.55	47.50	93.2		14.72	-	39.92**			
C-57	$[0/90_2/0]_{3T}$	12	.5661	.0092	n/a	12.07	52.60	69.00	.077	11.79	57.80	97.3		12.76	52.33	69.14			
C-60	$[0/90_2/0]_{3T}$	12	.5166	.0068	n/a	10.54	40.52	72.80	.025	10.80	48.81	88.0		12.17	47.73	80.45			
C-67	$[0/90_2/0]_{3T}$	12	.5634	.0068	Ave	12.73	††	63.88	.030	11.74	59.32	97.1	0.042	13.52	-	63.98	57.50	97.25	12.468
						Average			0.041				0.042	13.37	46.05	74.23	57.50	97.25	12.468
						Standard deviation			0.020				-	1.13	5.01	8.90	-	-	-

*$V_f = .6$, $V_v = .01$.

†Proportional limit values (based on transverse strain knee) except as noted.

‡No transverse gage.

**Panels had low Q.C. test results, not used in average, standard deviation values.

††No proportional limit recorded on transverse gage.

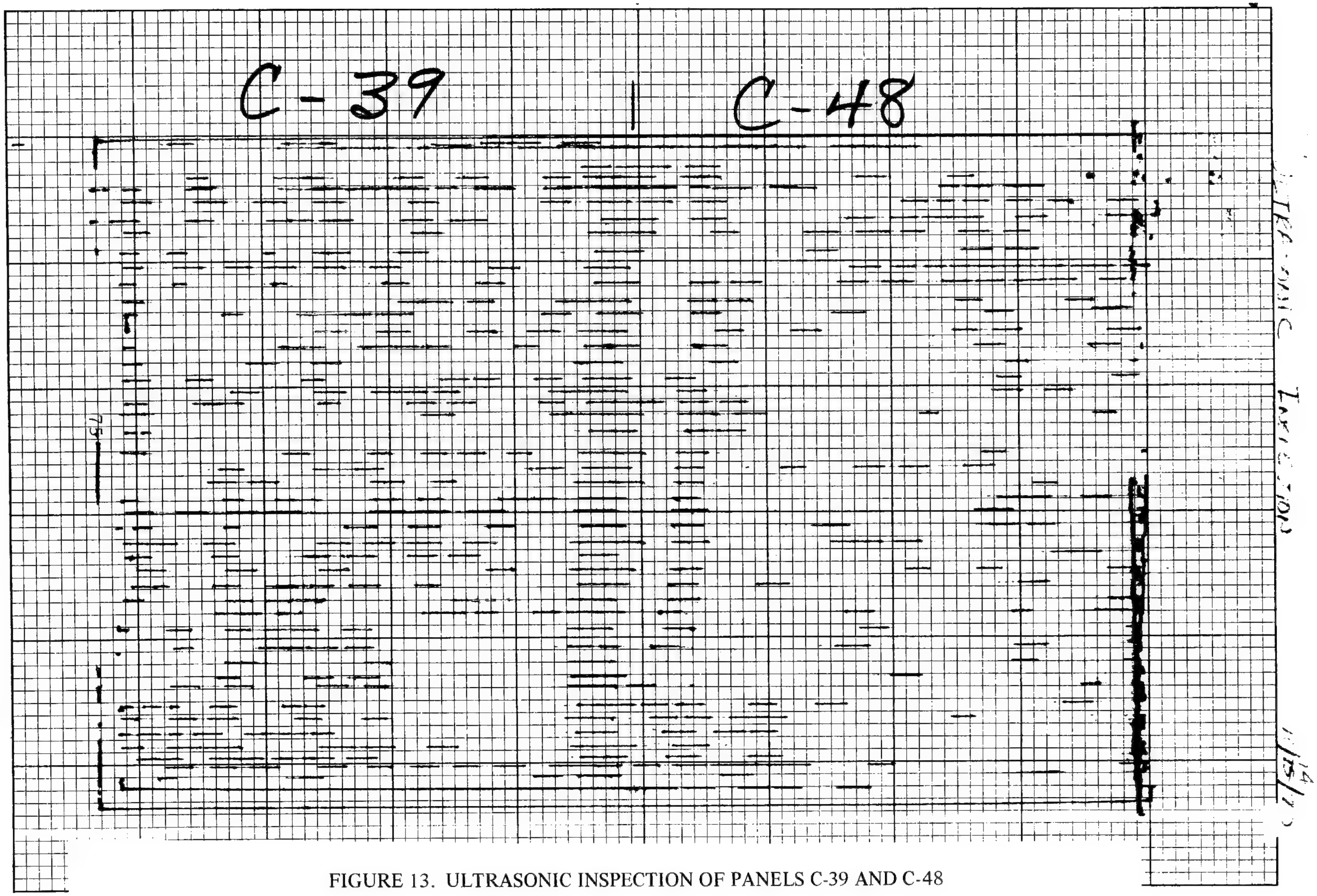

FIGURE 13. ULTRASONIC INSPECTION OF PANELS C-39 AND C-48

TABLE XXVI

$[0/90]_c$ NORMALIZED FLAT PANEL DATA SUMMARY (COMPRESSION)

						Experimental Data			Analytical Data			Normal Data					
Panel No.	Orientation	No. of Plies	Fiber Volume	Void Volume	Q. C. Test Results	E_{ex} psi	$\sigma_{ex}(P. L.)$ ksi	$\overline{\sigma}_{ex}(U)$ ksi	E_{cex} psi	$\sigma_{cex}(P.L.)$* ksi	$\overline{\sigma}_{cex}(U)$† ksi	E_{nex} psi	$\sigma_{nex}(P. L.)$ ksi	$\overline{\sigma}_{nex}(U)$ ksi	E_{cn} psi	$\sigma_{cn}(P. L.)$ ksi	$\overline{\sigma}_{cn}(U)$ ksi
C-40	$[0/90_2/0]_{3T}$	12	.5571	.0304	Ave	10.63 x 10^6	‡	76.49	11.60 x 10^6	60.79	74.00	11.42 x 10^6	-	83.72	12.468 x 10^6	64.91	81.00
C-57	$[0/90_2/0]_{3T}$	12	.5661	.0092	n/a	9.97 x 10^6	‡	80.25	11.79 x 10^6	61.83	77.00	10.54 x 10^6	-	84.42	12.468 x 10^6	64.91	81.00
											Avg.	10.98 x 10^6	-	84.07	12.468 x 10^6	64.91	81.00
											Std Dev.	0.622 x 10^6	-	0.50	-	-	-

*Based on maximum strain criteria using 0° lamina failure strain for compression.

†Micromechanics technique used.

‡No proportional limit recorded on longitudinal stress/strain curve, i.e., linear to failure, however, no longitudinal stress transverse strain curve was recorded.

recorded on compression specimens, no proportional limit values were observed. However, internal damage to the 0° plies of a $[0/90]_c$ specimen does occur at 70-80% of ultimate failure stress in compression. An examination of the $[0]_c$ specimens indicated that possible microbuckling along the side edges (indicated by a brooming of fibers at the unsupported edge) could be occurring causing failure of the specimen prematurely.* This free edge microbuckling does not occur in the $[0/90]_c$ specimens because of the added support of the 90° plies, thus allowing the laminate (especially the 0° laminas) to achieve their full strength. Discussions with AFML revealed their $[0]_c$ short column compression tests on the same material were running about 25% higher. With the SwRI U/TC compression specimen† it was found that a $[0]_{12T}$ laminate gave about 25% higher values than an $[0]_{18T}$ one after normalizing for fiber volume. The AFML short compression test gave about 50% higher results than the SwRI U/TC jig $[0]_{18T}$ results. So the values used are estimated to be approximately 25% below the $[0]_c$ fully stabilized compression strength values. A study was conducted using the AFML compression data to develop an empirical micromechanics strength prediction formula. Equation (2) resulted, and it predicts the AFML failure stresses well. For $[0/90]_c$ specimens, the values calculated by Equation (2) can be divided by 2 to get the predicted value. Using the SwRI 12-ply $[0/90]_c$ data, comparative results are shown in Table XXVII. This approach is considered justified because (1) there are an equal numer of equal thickness 0° plies and 90° plies, (2) the 90° plies are assumed to be in the plastic range (with no load carrying ability) at or near the ultimate $[0/90]_c$ specimen stress, and (3) therefore, the 0° plies are carrying all the load. Ultimate failure occurs in the 0° ply as a result of a stabilized, local microbuckling failure.‡

TABLE XXVII

STRESS PREDICTIONS BASED ON AFML UNIDIRECTIONAL COMPRESSION DATA

Panel No.	SwRI Exp Stress (ksi)	Predicted Value Using Equation 2 (ksi)
C-40	76.49	74.00
C-57	80.25	77.00

4. DEVELOPMENT OF CONFIDENCE LIMITS AND DESIGN ALLOWABLES FOR STATIC FLAT PANEL DATA

The generation of confidence limits and design allowables are dependent on two very important parameters, i.e., data scatter and number of tests conducted. Data scatter was minimized by utilizing only test data that had no observed irregulatities; either in the quality control tests or property tests. The $[0]_c$ laminates were evaluated with a minimum number of tests in both tension and compression, and as a result had relatively few "good" tests, therefore the "t" function in the C.L. and design allowables determination was large.

Calculation of the confidence intervals for the population mean ultimate and proportional limit tensile and compressive stresses and mean moduli consists of using the following equation:

$$90\%\ \text{Confidence Limits at } f = \bar{f} \pm \frac{ts}{\sqrt{n}} \tag{22}$$

$$90\%\ \text{Confidence Limits at } E = \bar{E} \pm \frac{ts}{\sqrt{n}} \tag{23}$$

*The effect was worse (failing stresses substantially lower) on 18-ply $[0]_c$ specimens than on 12-ply $[0]_c$ ones.

†Drawing No. 03-2776-01-3, Appendix IV

‡As opposed to the onset of microbuckling as measured on $[0]_{12T}$ specimen by the SwRI U/TC platen supported jig; as observed in the 0° plies of $[0/90_2/0]_{3T}$ specimens at 70-80% of ultimate and as predicted by maximum strain theory using the 0° ply microbuckling strain as the limit.

TABLE XXVIII

90% CONFIDENCE INTERVALS FOR NORMALIZED MODULUS AND ULTIMATE STRESS ON THE COURTAULD'S HTS/ERL 2256 GRAPHITE/EPOXY SYSTEM
(Fiber Volume = 0.60, Void Volume = 0.01)

		Confidence Interval			
		Modulus (x 10^6 Psi)		Stress (Psi)	
Orientation	Test Type	UCL_{90}*	LCL_{90}*	UCL_{90}	LCL_{90}
0°	Tension Compression	26.83 23.75	20.25 22.00	200,180 127,280	165,260 97,220
90°	Tension Compression	1.36 1.76	1.22 1.08	5,440 26,550	4,660 21,950
0/90°	Tension Compression	15.20 13.76	11.54 8.20	80,770 86,300	67,690 81,840

*LCL_{90} - Lower Confidence Limit

UCL_{90} - Upper Confidence Limit

where $\bar{f}$ is the normalized average proportional limit or failure stress (either tension or compression) and $\bar{E}$ is the normalized average modulus, n is the number of replicate tests, s is the standard deviation, and t is the t-devuate corresponding to the degrees of freedom in the sample (n-1). These limits define the interval within which the mean of a very large number of tests would probably lie relative to the mean of this experimental data. Confidence intervals for ultimate strength and modulus of the Courtauld's HTS/ERL 2256 system in orientations of $[0]_c$, $[90]_c$, $[0/90]_c$ are shown in Table XXVIII.

With the confidence limits established, it is possible to calculate 90% confidence design allowables in the following manner:

$$DA_{90} = LCL_{90} - ts \qquad (24)$$

where

$$LCL_{90} = \bar{f} - \frac{ts}{\sqrt{n}}$$ (lower confidence limit) and t, n, s have the same definitions as above

In essence, this calculation says that, if the population mean $\bar{f}$ did turn out to be at the lower confidence level, then about 5 of 100 specimens would fail at the design allowable stress level or lower. This is a conservative estimate; the real failure probabilities should be more favorable. Design allowables based on ultimate stress values are shown in Table XXIX. These values may seem low, but as more data becomes available the confidence intervals should narrow and thus the design allowables will increase.

TABLE XXIX

90% DESIGN ALLOWABLE BASED ON ULTIMATE STRESS FOR THE COURTAULD'S HTS/ERL 2256 GRAPHITE/EPOXY MATERIAL SYSTEM
(Fiber Volume = 0.60, Void Volume = 0.01)

Orientation	Loading	90% Design Allowable Stress (Psi)
0°	Tension Compression	135,000 67,140
90°	Tension Compression	3,510 13,360
0/90°	Tension Compression	50,400 78,680

The tension proportional limit* stress confidence limits and design allowables are LCL_{90} = 41,270 psi, UCL_{90} = 50,830 psi, and DA_{90} = 30,590 psi. Compression proportional limits were not observed because no transverse strain gages were used. However, damage was found (see Section IV.2) at this 70-80% of ultimate stress level (approximately equal to the $[0]_c$ experimental ultimate compression strain).

*Based on transverse strain knee, and observed onset of 90° ply cracking.

5. TESTING OF TUBULAR SPECIMENS

a. Experimental Procedures

Tubular specimens of four and eight ply thickness in $[0]_c$ and $[0/90_2/0]_c$ layups were fabricated and fitted with 30° or 45° beveled bonded steel tabs at each end for load transfer except for two which were fitted with wrapped fiberglas end tabs. The tubes were nominally ten inches long* with three, one hundred twenty degree (120°) by three-inch long tab sections bonded to each end. The test section was four inches long, 1.10 inches outside diameter and from 0.040 to 0.095 inch in wall thickness, depending upon the number of plies and their thickness. Steel fixtures were bolted to the end tabs of the specimen with six bolts on each end (two in each of the three tab sections). These fixtures provided the means of attachment of the specimen in the load frame and provided plumbing and seals for internal pressurization of the specimen.

All of the tests in torsion and tension/torsion were performed on an SwRI developed electro-hydraulic biaxial testing machine. This machine has two independent axes of loading with 10,000-pound axial and 6,800-inch-pound torsional load capacity. The loads are servo-controlled with feedback derived from either load, strain, or head displacement transducers. Figure 14 shows this facility in operation with a tubular specimen having wrapped fiberglas end tabs.

The tension and tension/internal pressure tests were performed on a larger electro-hydraulic servo-controlled SwRI testing facility having a capacity of 50,000 pounds axial load. The machine was equipped with a servo-controlled hydraulic intensifier capable of producing up to 20,000 psi pressure for loading the tube specimen internally. The controlled functions in these tests were loads.

Compression, internal pressure, and compression/internal pressure combinations were performed on a four range Baldwin Universal Test Machine utilizing standard hydraulic pump/gage pressurization techniques. For compression tests the loading was introduced with rigid parallel heads using clad aluminum bearing plates but with no mechanical attachment to the load tabs. For internal pressure tests a floating aluminum end plug with double "O" ring seals was used inside the silicone rubber tube through which the internal pressure was applied. The floating plugs were restrained in the Baldwin without introducing longitudinal loads into the specimen thereby achieving pure circumferential tension. Combined compression/internal pressure loadings utilized both techniques described above simultaneously. A constant load rate was used and the readings were taken by stopping loading for one second intervals, the time it takes to push the readout button and the readout to be accomplished.

Strain gages were attached to the gage section of each specimen. For the tension/torsion tests, three strain gage bridges were used to measure, independently, axial strain, transverse (hoop) strain, and torsional (shear) strain. Two sets of gages were used in both the axial and transverse directions for the tension and tension/internal pressure tests. These gages were used for strain measurement only. Because small cracks developing in the matrix of the specimen would upset the strain measurement prior to complete specimen failure, these gages could not be used for control signal. Figure 15 shows a specimen with gages attached, ready for testing. For compression tests three longitudinal gages (located 120° apart around circumference) were used with one circumferential gage (see Fig. 15). For internal pressure tests two circumferential and two longitudinal gages were used and for combined compression/internal pressure three longitudinal and three transverse gages were used.

All strains on twelve† of the tubes were measured with strain gages having gage length 1/8 inch, resistance 120Ω, bonded onto the outer surface of the specimen. The question arose as to whether these gages would generate sufficient heat to alter their response and thereby give a false reading. To answer this question, one specimen (CT-48) was instrumented both with 1/8-inch 120Ω gages and with 1/4-inch 350Ω gages, and the

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*Except for CT-7 which was 7 inches long (2-inch long tabs, 3-inch gage section).

†Tube Numbers CT-9, 14, 16, 17, 38, 39, 43, 45, 48, 49, 51, 57.

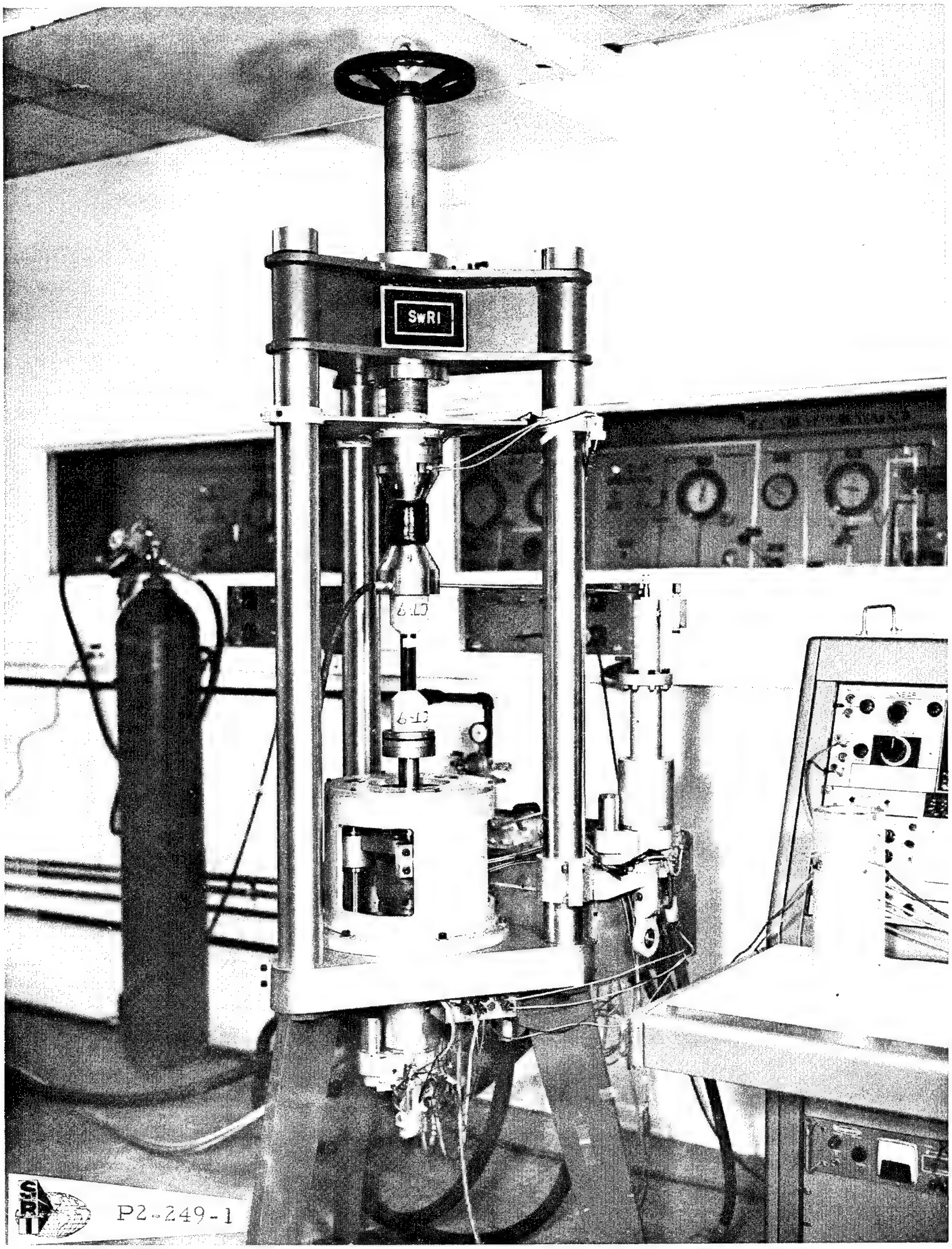

FIGURE 14. BIAXIAL TUBE TEST FACILITY

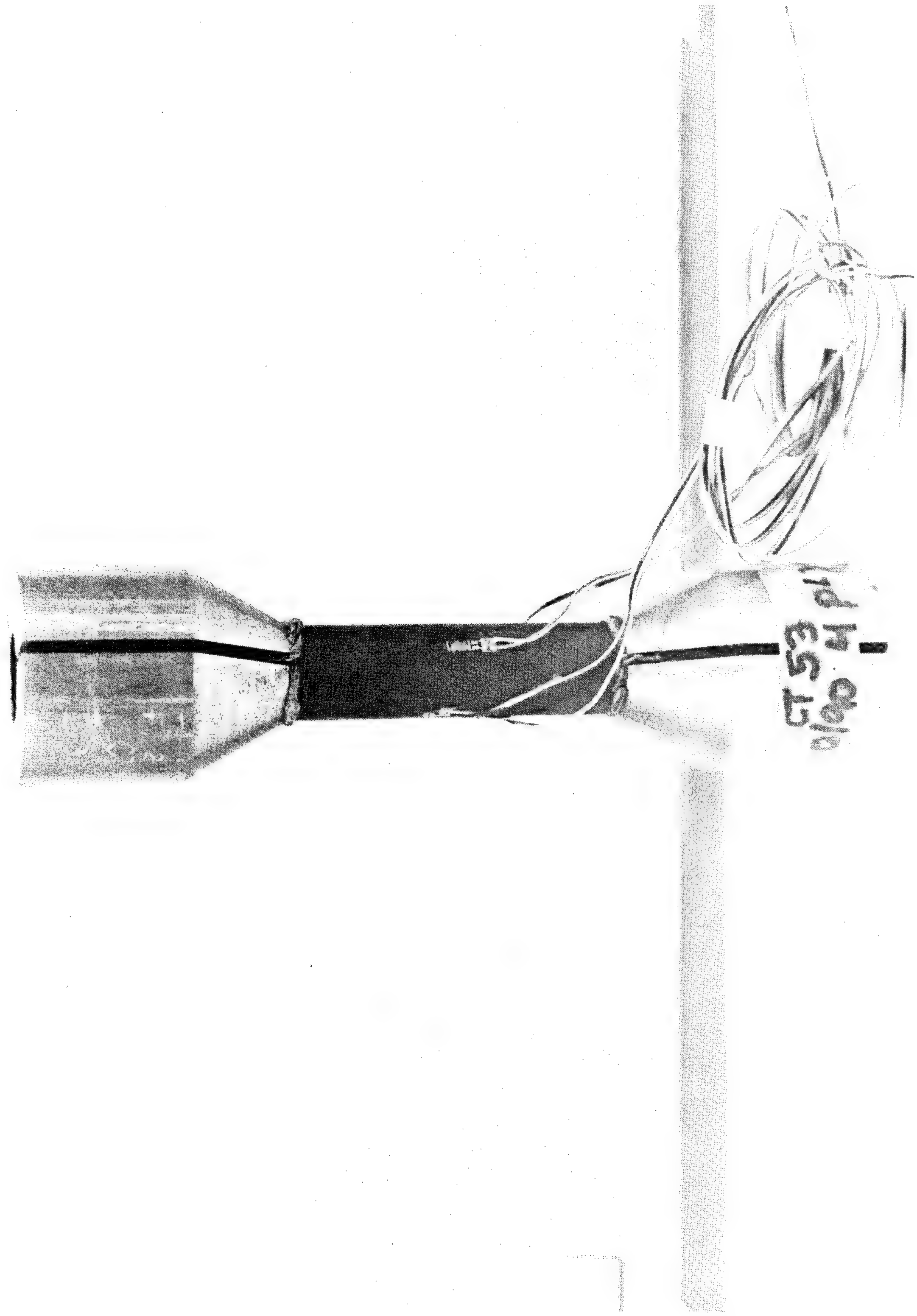

FIGURE 15. GAGED TUBE SPECIMEN (1/4 INCH, 350Ω GAGES)

responses compared. The response of the 350Ω gage as a function of 120Ω gage response was linear over the range tested (about 0.2% strain). Since adopting a higher resistance gage (generating less heat) did not affect the measured strains with the equipment* used, it was concluded that the 120Ω gages were giving true readings.

All strains on nine† of the tubes were measured with 1/4-inch long 350Ω resistance strain gages bonded onto the outer surface of the specimen. A B&F semi-automatic digital readout was used for the strain readout on these tests. For this equipment (B&F) the 1/4-inch 350Ω gages were found to give more accurate strain readings than the 1/16-inch 120Ω gages with which they were compared. The 1/16-inch 120Ω gages were found to give strain readings approximately 9% too high.

In the tension/torsion tests, performed in the biaxial testing machine, strain rate in the specimen was held essentially constant by controlling head displacement with a ramp function. In the biaxial tests deformation was controlled on one axis and a signal proportional to the load produced on that axis was used to control the load on the second axis. In this way a constant stress ratio was maintained.

The tension and tension/internal pressure tests conducted on the larger (50,000 pound) testing machine were done at constant load rate because head displacement feedback was not available. In tension the specimens are essentially elastic until fracture so that a constant load-rate produces a constant strain-rate. For combined loading the hoop-stress was controlled (either by the servo-intensifier, specimen CT-49, or by a manual pressure regulator, specimen CT-39) and a signal proportional to it used to control the axial load to produce a constant stress ratio.

A strip chart recorder was used to record the strain and load signals from each tension, torsion, tension/internal pressure and tension/torsion test. Compression, internal pressure, and compression with internal pressure tests utilized the B&F automatic digital data recording system described above and used in the flat panel specimen test program. Compression loads were applied with a four range Baldwin Universal Test Machine and internal pressure was applied with standard hydraulic pumps using water. Pressure was monitored and recorded from standard pressure gages. Axial tension and torsional loads were measured with a strain-gage load cell in series with the specimen. Hoop stress (for tension/internal pressure) was measured with a strain-gage pressure transducer.

b. Elastic State Description

Figure 16 illustrates the coordinate notation used in discussing the tube tests. x and θ are, respectively, the axial and circumferential directions. It is assumed that the thin tube configuration places the gage section of the specimen in a state of generalized plane stress:

$$\begin{pmatrix} \sigma_\theta \\ \sigma_\theta \\ \tau_{x\theta} \end{pmatrix} = \begin{pmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{pmatrix} \begin{pmatrix} \epsilon_x \\ \epsilon_\theta \\ \gamma_{x\theta} \end{pmatrix} \tag{25}$$

In the range where elastic behavior prevails, the Q_{ij} are (constant) components of the elastic stiffness matrix. There are four such components needed to characterize a homogeneous orthotropic material loaded by in-plane forces. In terms of the conventional engineering elastic constants:

$$\left.\begin{aligned} Q_{11} &= \frac{E_{11}}{1-\nu_{12}^2 E_{22}/E_{11}} & \qquad Q_{12} &= \frac{\nu_{12}E_{22}}{1-\nu_{12}^2 E_{22}/E_{11}} \\ Q_{22} &= \frac{E_{22}}{1-\nu_{12}^2 E_{22}/E_{11}} & \qquad Q_{66} &= G_{12} \end{aligned}\right\} \tag{26}$$

*Very low voltage strain gage pre-amp (part of servo-control system) used here. B&F Digital Strain Recorder not used here.

†Tube Numbers CT-7, 15, 37, 41, 42, 44, 46, 53, 59.

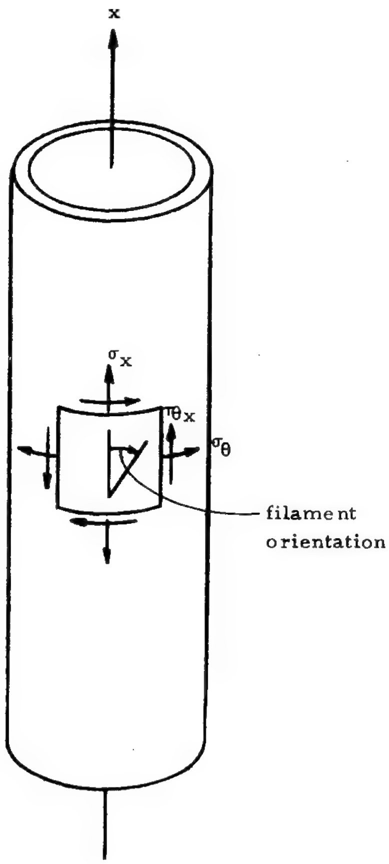

FIGURE 16. COORDINATE NOTATION FOR TUBES

Thus, the four independent stiffness constants for the orthotropic laminate are related to the four independent elastic constants E_{11}, E_{22}, ν_{12}, and G_{12}. The subscripting convention for the elastic constants is such that the "1" and "2" directions correspond with the "x" and "y" axes of the specimen, respectively. This correspondence can be made only in those cases where the material and specimen axes are coincident, as here.

In discussing results from tests involving combined states of stress one must be careful to make proper distinction between the slope of the measured stress-strain data, and the actual elastic constants. To illustrate this distinction, which arises when responses are coupled, suppose one performs an experiment involving combined tension and internal pressure loading. Let $\sigma_x = \sigma$ and $\sigma_\theta = \alpha\sigma$ be the stresses in the tube. The apparent modulus in the x-direction, $\partial\sigma/\partial\epsilon_x$, is

$$\frac{\partial\sigma}{\partial\epsilon_x} = \frac{Q_{11}Q_{22} - Q_{12}^2}{Q_{22} - \alpha Q_{12}} \tag{27}$$

and depends, therefore, upon the particular state of combined stress, α. Only when the loading is pure tension ($\alpha = 0$) does $\partial\sigma/\partial\epsilon_x = E_{11}$, the Young's modulus in the x-direction. Thus, the slopes of stress-strain curves taken from combined load tests do not, in general, give the elastic constants directly. The measured slopes do correspond to the constants when the loading modes are uncoupled as, e.g., for a symmetric orthotropic laminate loaded in tension/ torsion.

To determine the four elastic constants requires that, in general, four independent elastic tests be conducted. According to the assumed constitutive behavior the shear response is uncoupled from the direct stress response, and hence a test involving pure torsional loading will determine Q_{66} directly. Then, three tests in which the specimen is loaded by σ_x only, σ_θ only, and combined σ_x and σ_θ will serve to determine Q_{11}, Q_{12}, and Q_{22}.

Some preliminary tests were conducted on two tubes (CT-9 and CT-16) to find the stiffness constants. These results were incomplete because internal pressure loading was not available at the time the testing was being conducted, making it impossible to determine Q_{22}. In addition, the virtually complete absence of shear and normal stress coupling,* together with the lack of the internal pressure loading mode, made it difficult to determine Q_{11} and Q_{12} with any degree of accuracy from the tube test data.

Appendix III presents the detailed data relating to the stress-strain relations and physical characteristics of the tubes. Using these data, one may calculate the stiffness coefficients for those specimens which were loaded in a single mode only, or were loaded in combined but uncoupled modes (e.g., tension/torsion). These stiffness coefficients are summarized in Table XXX. The scatter in Q_{66} is relatively larger than in Q_{11} or Q_{22}. This is attributed to the very small region of true linearity in torsion, and to the difficulty in measuring the slopes of the stress-strain curves accurately in the linear region.

c. Failure State Description

A total of 21 tubes were tested to failure in various states of tension, compression, torsion, internal pressure, and proportional combinations thereof. Table XXXI summarizes the type of test performed on each of

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*A very small amount of shear-normal stress coupling was found in Specimen CT-16. See the remarks in Appendix III.

TABLE XXX

SUMMARY OF TUBE STIFFNESS COEFFICIENTS

Spec No.	Layup	Fiber Vol. (%)	Q_{11} (x 10^6 psi)	Q_{22} (x 10^6 psi)	Q_{66} (x 10^6 psi)
CT-7	$[0]_{4T}$	42.34	15.8 (c)		
9	$[0]_{4T}$	47.93			0.646
14	$[0]_{4T}$	54.96			
16	$[0]_{4T}$	47.81			0.535
17	$[0]_{4T}$	45.55	27.0		0.252
37	$[0]_{8T}$	50.70		1.14	
38	$[0]_{8T}$	52.65	21.3		
41	$[0]_{8T}$	55.01	21.4 (c)		
43	$[0/90_2/0]_T$	51.02			1.54
44	$[0/90_2/0]_{2T}$	53.22	10.7 (c)		
45	$[0]_{4T}$	56.22	21.9		
48	$[0]_{4T}$	50.92	20.3		
51	$[0/90_2/0]_T$	53.52	13.3		0.645
53	$[0/90_2/0]_T$	47.60		10.0	
57	$[0/90_2/0]_T$	49.92	10.4		
59	$[0/90_2/0]_T$	53.20	9.3 (c)		

(c) = compression

TABLE XXXI

TUBE FAILURE MODES

Spec No.	Layup	Failure Loading*	Predominant Crack Direction†	Presence of Failure Near End Tabs?	Delamination Present?	Adhesive Failure In Tab?
CT-7	$[0]_{4T}$	LC	M	yes	locally	no
9	$[0]_{4T}$	TOR	M	yes	very little	no
14	$[0]_{4T}$	LT	M	no	locally	no
15	$[0]_{4T}$	IP	F	no	very little	no
16	$[0]_{4T}$	TOR	F	yes	very little	no
17	$[0]_{4T}$	LT/TOR (1:1)	M	yes	widespread	no
37	$[0]_{8T}$	IP	F	(no tabs used)	very little	(no tabs used)
38	$[0]_{8T}$	LT	M	no	very little	no
39	$[0]_{8T}$	LT/IP (1:1)	M	yes	widespread	no
41	$[0]_{8T}$	LC	F	yes	very little	no
42	$[0/90_2/0]_T$	LC/IP (1:1)	F	yes	very little	no
43	$[0/90_2/0]_T$	TOR	M	no	widespread	no
44	$[0/90_2/0]_{2T}$	LC	M	no	widespread	no
45	$[0]_{4T}$	LT	F	no	very little	yes
46	$[0]_{8T}$	LC/IP (1:1)	F	no	very little	no
48	$[0]_{4T}$	LT	M	no	very little	no
49	$[0/90_2/0]_T$	LT/IP (1:1)	M	no	locally	no
51	$[0/90_2/0]_T$	LT/TOR (2:1)	M	yes	widespread	no
53	$[0/90_2/0]_T$	IP	M	no	locally	no
57	$[0/90_2/0]_T$	LT	M	yes	very little	no
59	$[0/90_2/0]_T$	LC	M	no	locally	no

*Code

LT = Longitudinal Tension
LC = Longitudinal Compression
TOR = Torsion
IP = Internal Pressure

†Code

F = Fiber Direction
T = Transverse to F
M = Mixed F & T

TABLE XXXII

SUMMARY OF TUBE FAILURE STATES

Spec No.	Stresses at Failure (ksi) σ_x	σ_θ	$\tau_{x\theta}$	Strains at Failure (%) ϵ_x	ϵ_θ	$\gamma_{x\theta}$	Comments
CT-7	-87.56			-0.580	0.495		
9	--		10.5	*	*	4.30	
14	89.0		--	0.450	*	--	
15	--	0.57	--	*	*	--	
16	--	--	7.57	*	*	2.39	
17	6.02	--	6.8	-0.006	-0.052	2.70	
37	--	2.86	--	-0.0054	0.251	--	
38	68.0	--	--	0.320	-0.153	--	
39	3.99	3.77	--	0.0206	0.322	--	
41	-134.4	--	--	-0.653	0.220	--	
42	-6.59	5.45	--	-0.0815	0.0338	--	
43	--	--	11.9	-0.300	-0.30	7.30	max $\tau_{x\theta} = 12.5$
44	-66.62	--	--	-0.848	0.0474	--	
45	67.0	--	--	0.305	*	--	debonded at grip
46	-2.59	2.50	--	-0.0091	0.155	--	
48	98.0	--	--	0.405	-0.128	--	
49	37.6	37.2	--	0.606	0.305	--	
51	25.2	--	11.9	0.188	-0.150	4.0	failure at grip terminus
53	--	28.68	--	0.0250	0.310	--	
57	55.4	--	--	0.515	-0.038	--	failure at grip terminus
59	-56.37	--	--	-0.655	0.160	--	

* not measured

these specimens along with qualitative indices of the failure mode. Photographs detailing the failure modes are presented in Appendix III. As shown in Table XXXI, the end tabs and gripping arrangement did influence the failure state in a number of the tests; this problem is discussed more fully later in this section. It should be remarked at this point, however, that in those experiments where grip effects were apparent, the stress and strain states at failure are not indicative of the material behavior.

Table XXXII gives a summary of the stress and strain states at failure. No attempt has been made to develop failure surface representations from the tube data only, owing to the small number of test points for each particular layup used, and to the disturbing influence of the grip effects in a number of the experiments. In analogy to biaxial failure representations for isotropic materials, one can conceive of a failure surface in stress (or strain) space for laminated composites. The convenience of representing the failure for isotropic materials in the principal stress (strain) plane, however, is lost with anisotropic materials. Failure data for thin laminated tubes must be presented in terms of three independent variables, such as σ_x, σ_θ, $\tau_{x\theta}$, or the two principal stresses and the angle of orientation between the material and loading axes.

The following observations are made in connection with the failure modes of the tubular specimens.

(1) All specimens suffered some fracture across the fibers; in no case was failure confined entirely to the matrix

(2) There were no layups or loading modes which were immune from some delamination.* Longitudinal splitting delamination of all 0° tubes loaded in tension was observed

(3) In all but one case (CT-42) the 0°/90° specimens failed by a balanced mixture of filament and matrix fracture. Approximately half of the 0° specimens experienced such a mixed mode failure

(4) In all but one case (CT-43) those specimens loaded in torsion failed in a mode which appeared to be influenced by the end tabs

*Delamination defined as matrix fracture and/or lamina debonding in any plane.

(5) In all 0° specimens loaded in tension the end tabs did not appear to influence strongly the fracture mode. In one of the 0°/90° tubes tested in tension (CT-57), the end tabs did influence the fracture mode*

(6) From the previous two observations, for 0° tubes, the end tabs influence the fracture mode more significantly in torsion than in tension*

d. Load Introduction

The problem of providing a suitable grip for loading the laminated tube continues to be a problem. Ideally, the grip should be capable of transmitting the required loads in a manner so as not to create deleterious stress concentrations in the specimen due to geometric discontinuities or strain incompatibilities at the grip/specimen interface. Also, the loads must be introduced so as to diffuse the stresses rapidly and uniformly across the wall thickness. Unless these conditions are adequately met, the grip will itself influence the mechanical response of the loaded tube, thereby giving misleading values for stiffness coefficients and the failure state.

The gripping arrangement used in the present investigation, just described, falls somewhat short of meeting these requirements. Many of the failures occurred at, or very near to, the grip (see Table XXXI), indicating an aggravated strain distribution and probable premature failure. Steps are being taken to alleviate this problem. Meanwhile, the tube properties data reported here must be used with discretion in view of the grip influence.

e. Normalization of Tube Data and Generation of Partial Failure Surfaces

(1) Tube Data

Thirteen $[0]_c$ tubes were tested in the program; eight were subjected axial or circumferential loads and five were subjected to biaxial loadings.

Axial and circumferential loading $[0]_c$ tube data are shown in Table XXXIII. As previously noted, the longitudinal tensile strengths achieved with these tubes were not on par with the flat specimen data, even when normalized. The cause of this was not determined but the tab design and load introduction technique was suspected. Compression data were judged to be good and when normalized were above flat specimen results, though not quite up to the estimated stabilized (or short column) compression strength.† Elastic properties were in excellent agreement with the flat specimen data, and primary Poisson's ratio values correlated well with the predicted values.‡ Circumferential (transverse) tension strength values (internal pressure loading without longitudinal loading) were slightly below the flat specimen data but may well be within experimental scatter.

A summary of the actual and normalized experimental results and the actual and normalized analytical predictions are shown in this table (XXXIII) for $[0]_c$ tubes loaded axially or circumferentially. Except for the aforementioned tensile strengths the correlation with predicted values is reasonably good or as good as was obtained with flat specimen data.

Biaxial test data were obtained on five $[0]_c$ tubes covering pure torsion (2 tubes), tension/torsion (1 tube), tension/internal pressure (1 tube) and compression/internal pressure (1 tube). Actual and normalized experimental results and actual and normalized analytical predictions for these tubes are presented in Table XXXIV. Torsion tube elastic and strength properties were judged to be good, as the elastic properties correlate with analytical predictions. The quality of the tension/torsion, tension/internal pressure, and compression/internal pressure data are unknown. For purposes of drawing a failure surface it is assumed that the data is acceptable.

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*Analytical studies indicate just the opposite conclusions.

†Estimated to be in the neighborhood of 150-160 ksi for 0.60 F.V. and 0.01 V.V.

‡No experimental data were obtained on the $[0]_c$ primary Poisson's ratio values from flat specimens.

TABLE XXXIII

$[0]_c$ TUBE NORMALIZED AXIAL AND CIRCUMFERENTIAL RESULTS

Tube No.	Loading Mode	$\sigma_{\ell x_{PL}}$, ksi	$E_{\ell x}$, 10^6 psi	$\nu_{\ell\theta x}$	$\sigma_{\ell x_{ULT}}$, ksi	$\sigma_{\theta x_{PL}}$, ksi	$E_{\theta x}$, 10^6 psi	$\nu_{\theta\ell x}$	$\sigma_{\theta x_{ULT}}$, ksi
					Actual Experimental Results *				
CT-7	LC	-49.83†	15.80	0.664‡	-87.56	---	---	---	---
CT-14	LT	22.00	18.33	---	89.00	---	---	---	---
CT-15	TT(IP)	---	---	---	---	---	---	---	0.57
CT-37	TT(IP)	---	---	---	---	---	1.14	0.0215	2.86
CT-38	LT	55.00	21.30	0.516	68.00	---	---	---	---
CT-41	LC	-70.42	21.40	0.314	-134.40	---	---	---	---
CT-45	LT	---	21.90	---	67.00	---	---	---	---
CT-48	LT	46.30	20.30	0.311	98.00	---	---	---	---
					Normalized Experimental Results				
CT-7	LC	67.06	22.17	---	-116.93	---	---	---	---
CT-14	LT	23.74	19.96	---	103.60	---	---	---	---
CT-15	TT(IP)	---	---	---	---	---	---	---	---
CT-37	TT(IP)	---	---	---	---	---	1.18	---	2.740
CT-38	LT	61.87	24.19	---	76.16	---	---	---	---
CT-41	LC	50.11	22.87	---	-144.62	---	---	---	---
CT-45	LT	---	23.33	---	75.38	---	---	---	---
CT-48	LT	53.78	23.82	---	132.20	---	---	---	---

	$\sigma_{\ell a_{PL}}$, ksi	$E_{\ell a}$, 10^6 psi	$\nu_{\ell\theta a}$	$\sigma_{\ell a_{ULT}}$, ksi	$\sigma_{\theta a_{PL}}$, ksi	$E_{\theta a}$, 10^6 psi	$\nu_{\theta\ell a}$	$\sigma_{\theta a_{ULT}}$, ksi
				Analytical Predictions				
CT-7	---	16.826	0.332	-92.067	---	---	---	---
CT-14	---	21.680	0.1112	180.283	---	---	---	---
CT-15	---	---	---	---	---	1.016	0.0220	5.977
CT-37	---	---	---	---	---	1.058	0.0220	5.723
CT-38	---	20.971	0.1066	172.914	---	---	---	---
CT-41	---	21.698	0.324	-114.252	---	---	---	---
CT-45	---	22.163	0.1137	183.384	---	---	---	---
CT-48	---	20.126	0.1032	167.464	---	---	---	---
				Normalized Analytical Predictions				
CT-7	---	23.62	0.320	-122.947	---	---	---	---
CT-14	---	23.62	0.320	194.500	---	---	---	---
CT-15	---	---	---	---	---	1.189	---	5.483
CT-37	---	---	---	---	---	1.189	---	5.483
CT-38	---	23.62	0.320	194.500	---	---	---	---
CT-41	---	23.62	0.320	-122.947	---	---	---	---
CT-45	---	23.62	0.320	194.500	---	---	---	---
CT-48	---	23.62	0.320	194.500	---	---	---	---

* See Appendix III

† Transverse strain became nonlinear at 37.8 ksi and was approximately equal to longitudinal strain at failure stress.

‡ High ν may be caused by local micro-instability of fibers.

TABLE XXXIV

$[0]_c$ TUBE NORMALIZED BIAXIAL RESULTS

Tube No.	Loading Mode	$\tau_{\ell\theta x_{PL}}$, ksi	$Q_{66_x} = G_{\ell\theta x}$, 10^6 psi	$\tau_{\ell\theta x_U}$, ksi	$\sigma_{\ell x_{PL}}/\sigma_{\theta x_{PL}}$, ksi	Q_{11x}, 10^6 psi	Q_{12x}, 10^6 psi	Q_{22x}, 10^6 psi	$\sigma_{\ell x_U}/\sigma_{\theta x_U}$, ksi
					Actual Experimental Results*				
CT-9	TOR	1.00	0.646	10.50	---	---	---	---	---
CT-16	TOR	1.00	0.535	7.57	---	---	---	---	---
CT-17	(LT/TOR)(1:1)	---	0.252	6.80	2.70/0	27.00	---	---	6.02/0
CT-39	(LT/IP)(1:1)	---	---	---	---	23.52†	0.649†	1.26†	3.99/3.77
CT-46	(LC/IP)(1:1)	---	---	---	---	21.11†	0.360†	1.15†	-2.59/2.50
					Normalized Experimental Results				
CT-9	TOR	1.467	0.898‡	13.16‡	---	---	---	---	---
CT-16	TOR	1.472	0.745‡	9.45‡	---	---	---	---	---
CT-17	(LT/TOR)(1:1)	---	---	---	3.55‡/0	33.6	---	---	7.91‡/0
CT-39	(LT/IP)(1:1)	---	---	---	---	31.52	0.713	1.54	4.60‡/4.36‡
CT-46	(LC/IP)(1:1)	---	---	---	---	24.55	0.394	1.34	-290/280

	$\tau_{\ell a_{PL}}$, ksi	$Q_{66_x} = G_{\ell\theta a}$, 10^6 psi	$\tau_{\ell\theta a_U}$, ksi	$\sigma_{\ell a_{PL}}/\sigma_{\theta a_{PL}}$, ksi	Q_{11a}, 10^6 psi	Q_{12a}, 10^6 psi	Q_{22a}, 10^6 psi	$\sigma_{\ell a_U}/\sigma_{\theta a_U}$, ksi
				Analytical Predictions				
CT-9	---	0.553	---	---	---	---	---	---
CT-16	---	0.551	---	---	---	---	---	---
CT-17	---	0.519	---	---	20.00	---	---	---
CT-39	---	---	---	---	20.903	0.345	1.056	---
C-46	---	---	---	---	21.414	0.347	1.071	---
				Normalized Analytical Predictions				
C-9	---	0.811	---	---	---	---	---	---
C-16	---	0.811	---	---	---	---	---	---
C-17	---	0.811	---	---	24.902	---	---	---
C-39	---	---	---	---	24.902	0.380	1.253	---
C-46	---	---	---	---	24.902	0.380	1.253	---

Note: Results based on micromechanics normalization unless otherwise noted.

*See Appendix III.

†Data obtained from Table III.2 using fiber volume ratios.

‡Normalized using fiber volume ratios.

Utilizing the normalized longitudinal and transverse tension and compression experimental data* from subsection 3 along with the tension/internal pressure and the compression/internal pressure normalized tube data of Table XXXIV, the partial lamina failure surface at zero shear was drawn as shown in Figure 17. It is apparent from this curve that data points are needed with $[0]_c$ tubes loaded at longitudinal/transverse tension stress ratios of approximately 100:1, 25:1 and 5:1 to verify the curve of quadrant 1. Longitudinal compression/transverse tension stress ratios of approximately 120:1, 40:1 and 13:1 are also needed to verify the curve of quadrant 2. Quadrant 3 needs longitudinal/transverse compression stress ratio tube tests at approximately 3:1, 8:1 and 20:1 whereas quadrant 4 needs longitudinal tension/transverse compression data at approximately 1:1 and other ratios to be determined after the first test.

*Flat specimen data.

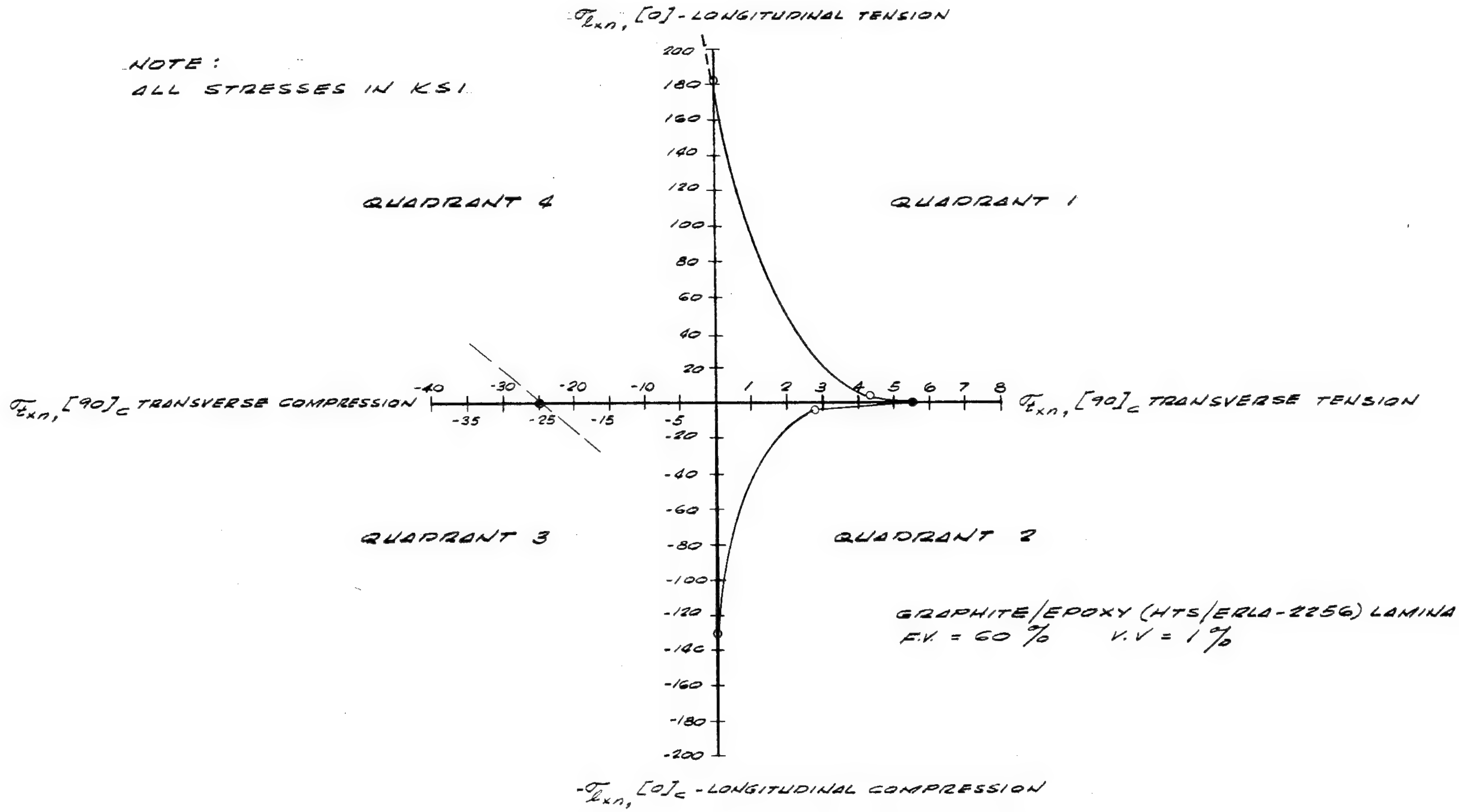


FIGURE 17. GRAPHITE/EPOXY LAMINA PARTIAL EXPERIMENTAL FAILURE SURFACE AT ZERO SHEAR

(2) $[0/90]_c$ Tube Data

Eight $[0/90]_c$ graphite/epoxy tubes were tested under axial, circumferential, and biaxial loading conditions, i.e., longitudinal tension (1 tube), longitudinal compression (2 tubes), circumferential tension (internal pressure) (1 tube), torsion (1 tube), longitudinal tension/circumferential tension (internal pressure) (1 tube), longitudinal compression/circumferential tension (internal pressure) (1 tube), and longitudinal tension/torsion (1 tube).

Figure 18 shows the partial failure surface at zero shear for Courtauld's HTS/ERL 2256, $[0/90]_c$ orientation composite materials. The $+\sigma_x$ refers to $[0/90]_c$ tension, $-\sigma_x$ is $[0/90]_c$ compression. $+\sigma_y$ refers to $[90/0]_c$ tensile results. The intercepts were determined from the average normalized flat panel and tube data generated. Limited $[90/0]_c$ compression tests indicated the $-\sigma_y$ values equal to the $-\sigma_x$ values at the intercepts. To obtain the points in the combined load regime, tube data generated was normalized and plotted in the appropriate quadrant. The method of normalization was exactly as was used in the flat panel data. Table XXXV shows the comparison of experimental and analytical along with the normalized data. Only one point was available to form the failure surface in the first quadrant, that of combined longitudinal and transverse (circumferential) tension. Another data point which was deemed useful was Tube CT-51 (longitudinal tension and torsion). It provides a point out on the Z-axis of the envelope but additional test data will be necessary to generate a failure surface at this shear level. Tube CT-42 (longitudinal compression and internal pressure) would have supplied a point in the fourth quadrant but premature failure occurred (cause noted in Table XXXV).

Partial failure surfaces for the experimental ultimate and damage level (proportional limit) strengths are shown in Figure 18. Analytically predicted damage level stresses (proportional limits) utilized maximum strain theory.

Straight lines used to generate these partial surfaces were used to indicate the general shape based on limited data and are felt to be conservative. It is obvious that additional data points are needed in Quadrant 1 whereas several data points are needed in each of the other three (2, 3, and 4) Quadrants to establish the failure surface shape.

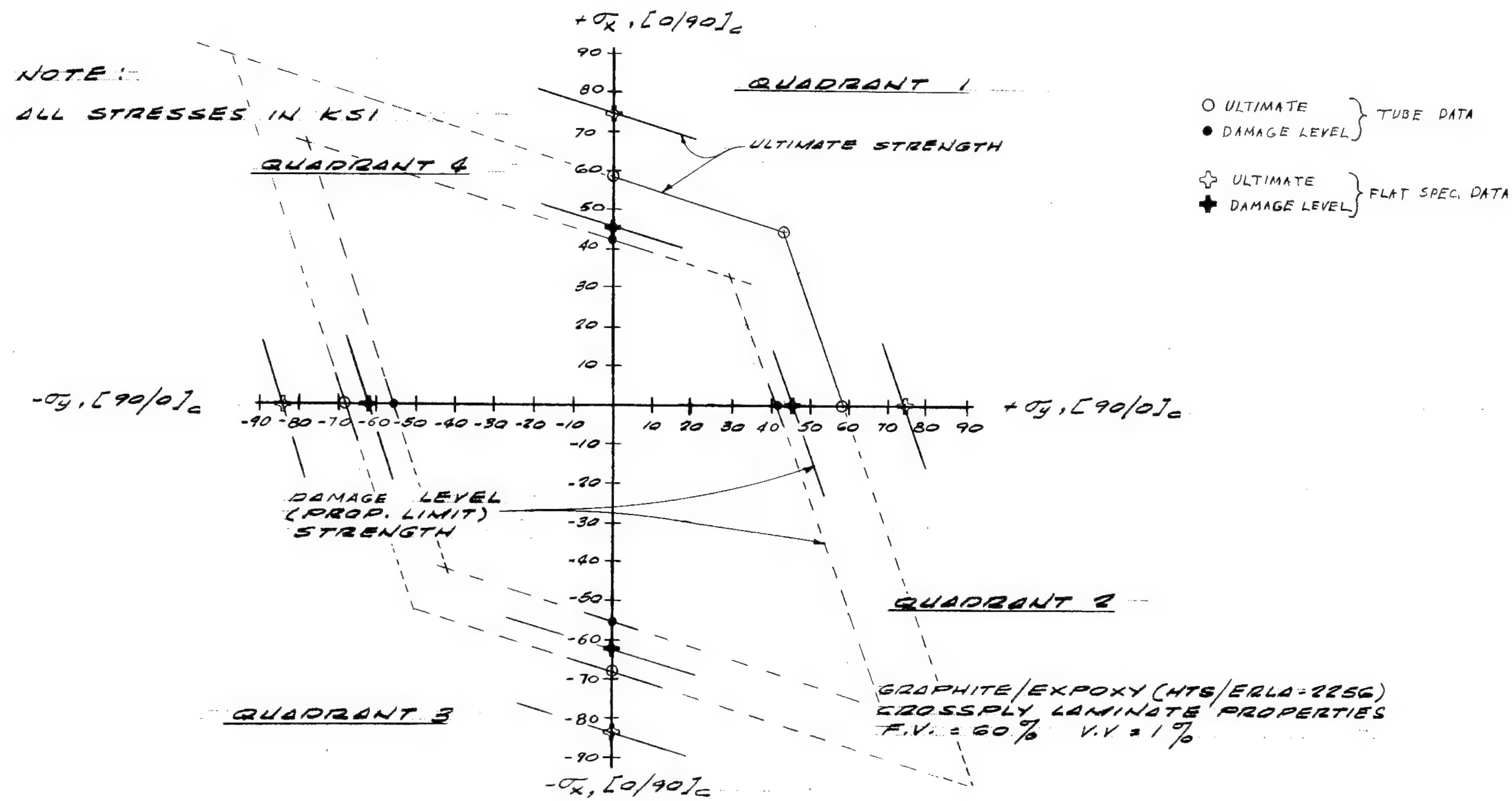


FIGURE 18. PARTIAL EXPERIMENTAL FAILURE SURFACE AT ZERO SHEAR FOR $[0/90]_c$ LAMINATES BASED ON NORMALIZED DATA

TABLE XXXV

$[0/90]_c$ TUBE TEST DATA NORMALIZATION SUMMARY

Tube No.	Type of Test	Experimental Data*						Analytical Data*						Normalized Analytical Data (V_f = .60, V_v = .01)						Normalized Experimental Data (V_f = .60, V_v = .01)					
		σ_{xex}	E_{xex}	$\sigma_{\theta ex}$	$E_{\theta ex}$	$\tau_{x\theta ex}$	$G_{x\theta ex}$	σ_{xc}	E_{xc}	$\sigma_{\theta c}$	$E_{\theta c}$	$\tau_{x\theta}$	$G_{x\theta}$	σ_{xn} †	E_{xn}	$\sigma_{\theta n}$ †	$E_{\theta n}$	$\tau_{x\theta n}$	$G_{x\theta n}$	σ_{xexn}	E_{xexn}	$\sigma_{\theta exn}$	$E_{\theta exn}$	$\tau_{x\theta exn}$	$G_{x\theta exn}$
CT-42	LC/IP(1)	-6,590	-	5,450	-	-	-	-56,193	10.68	-56,193	10.94	-	-	-64,910	-	57,503	12.47	-	-	-7,612	-	5,577	-	-	-
CT-43	TOR	-	-	-	-	11,900	1.54	-	-	-	-	4,402	.603	-	-	-	-	8,656	.766	-	-	-	-	23,400	1.96
CT-44	LC	-66,620‡	10.7	-	-	-	-	-58,628	11.10	-	-	-	-	-64,910	12.47	-	-	-	-	-73,758	12.02	-	-	-	-
CT-49	LT/IP	37,600	-	37,200	-	-	-	49,260	9.97	49,260	9.97	-	-	57,503	12.47	57,503	12.47	-	-	43,891	-	43,424	-	-	-
CT-51	LT/TOR	25,200	13.30	-	-	11,900	.645	58,746	11.16	-	-	2,600	.650	57,503	12.47	-	-	8,656	.766	24,667	14.86	-	-	39,618	0.760
CT-53	IP(2)	-	-	28,680	10.0	-	-	-	-	57,933	9.99	-	-	-	-	57,503	12.47	-	-	-	-	28,467	12.48	-	-
CT-57	LT	55,400**	10.40	-	-	-	-	55,179	10.45	-	-	-	-	57,503	12.47	-	-	-	-	57,732	12.41	-	-	-	-
CT-59	LC	-56,370††	9.30	-	-	-	-	-58,635	11.10	-	-	-	-	-64,910	12.47	-	-	-	-	-62,402	10.45	-	-	-	-

*See Appendix III and Section II for actual physical properties.

†These values are really proportional limit predictions for axial and circumferential loads based on maximum strain theory. Axial/internal pressure combined load test data not applicable.

‡Proportional limit at 50,740 psi (56,176) on transverse strain curve.

**Proportional limit = 40,000 psi (41,684)

††Proportional limit at 49,260 psi (54,531), lower (than CT-44) failure may be caused by local micro-instability since this was 4-ply tube.

Notes: 1. Premature failure caused by not using pressure bag liner.
2. Premature failure caused by pressure bags leaking to tube wall.

SECTION IV

SIGNIFICANT DAMAGE STRESS LEVEL EVALUATION

1. GENERAL

The purpose of this section is to present the results of the experimental study made to determine if various types of loading conditions caused significant changes in mechanical behavior of graphite/epoxy specimens and if significant micromechanical damage can be observed. A corollary to this is that any damage discovered is to be related to changes in mechanical behavior, if possible.

Section 2 covers the initial tension/subsequent tension and the initial compression/subsequent compression loading sequence data and damage observations. The initial tension/subsequent compression and the initial compression/subsequent tension load sequence data and damage study are presented in Section 3. Section 4 covers the tensile fatigue and residual strength data generated whereas Section 5 gives the tension and compression incremental loading and damage study data.

2. INITIAL/SUBSEQUENT TENSION AND INITIAL/SUBSEQUENT COMPRESSION STATIC LOAD DATA

A summary of the experimental data generated on these axially loaded damage level composite specimens is presented in Table XXXVI. These exploratory tests were performed to determine if specimens loaded to high (non-failure) stress levels sustained any visible or measurable micromechanical damage which might cause a reduction in properties as measured on subsequent static loading to failure.

Twelve $[0/90]_S$ graphite/epoxy specimens taken from two panels were initially loaded in tension to stress levels ranging from 55.3% to 83.05% of their average static ultimate tensile strength. Six of these (64-A, C, D, G, K, N) specimens (loaded to 77.7% F_{TU}) were subsequently loaded to failure (see Table II.15 of Appendix II). A typical stress-strain curve from these specimens is shown on page II.3.3 of Appendix II.3 with the failure photograph shown on page II.3.3. The only subsequent loading significant change observed was a reduction of transverse strain resulting in a substantially reduced Poisson's Ratio.*

Six other specimens were initially loaded in tension, but not failed, in order to be subsequently sectioned and investigated microscopically for damage. The first two (63-P, C) were loaded to 55.3% of ultimate tensile strength, sectioned and studied microscopically. Sectioning was performed at or near the geometric center of the specimens through the strain gages. Figure 19 summarizes the microscopic examination of Specimens 63-P, C which shows no micromechanical damage. Note also that these specimens (see pages II.3.4 and 5 of Appendix II.3) did not exhibit a knee (P.L.) in the stress-transverse strain curve. Specimens 64-F and M were loaded to 78.3% of the ultimate tensile strength, sectioned and studied microscopically with the results shown in Figure 20. The big difference in these specimens from the previous (lower load) ones is the appearance of major cracks traveling continuously across one transverse ply (see longitudinal cross-section) with the same type crack appearing in the adjacent transverse ply, slightly offset from the other crack and not contiguous with it. Data tabulation and a typical stress-strain curve for 64-F and M are given on page II.3.5 and 6 of Appendix II.3. Note that these specimens did exhibit proportional limit knees at 53.9% F_{TU}. Specimens 63-H and R were loaded to 83.05% F_{TU}, sectioned, and observed microscopically. These observations are summarized in Figures 21 and 22 for Specimens 63-H and R, respectively. While both specimens had proportional limit knees on the transverse strain curve at 64.2% F_{TU}, only 63-R (Fig. 22) showed the transverse ply cracking (longitudinal cross-section) described above for Specimens 64-F and M. Specimen 63-H (Fig. 21) showed no micromechanical damage in the sections taken. It is possible that the transverse ply cracking occurred away from the center section of the specimen which was observed. Pages II.3.7 and 8 of Appendix II.3 give the test data and stress-strain curves on these specimens.

*About one-half the original value.

TABLE XXXVI

INITIAL/SUBSEQUENT TENSION TEST AND COMPRESSION TEST DATA SUMMARY

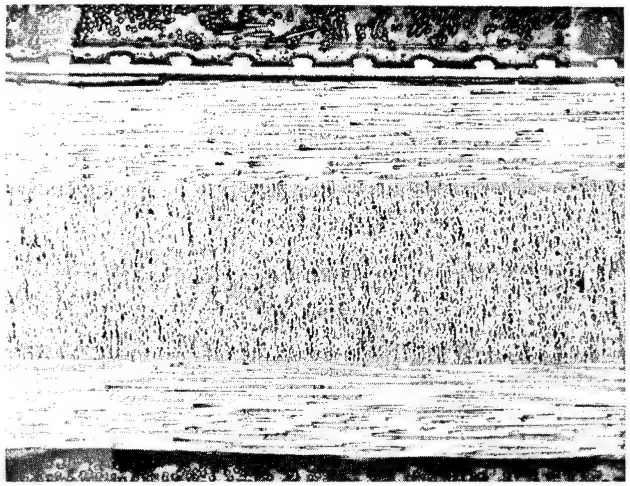
Panel No.	Specimen Nos.	Density lbs/in.^{3}	% Fiber Vol.	% Void Vol.	Lamination Code	Ply Thick. in.	Initial Loading Proportional Limit Stress, ksi @ Long. S.G.*	Initial Loading Proportional Limit Stress, ksi @ Trans. S.G.*	Initial Loading Stress, ksi	Initial Loading Poisson's Ratio	Initial Loading Modulus of Elast., 10^6 psi	Subsequent Failure Load Strength, ksi	Subsequent Failure Load Poisson's Ratio	Subsequent Load Mod. of Elast., 10^6 psi	Type Failure	Comments
									- Initial/Subsequent Tension -							
C-64	64-A, C, D, G, K, N	0.0559	58.37	0	$[0/90]_S$	0.00910	-	48.74 ($58.8\%F_{TU}$)	67.910 ($77.7\%F_{TU}$)	0.0253	11.67	81.01	0.0134	12.13		Large ult. strength and Poisson's Ratio scatter
C-63	63-P, C	0.0560	58.77	0.02	$[0/90]_S$	0.00900	-	-	42.932 ($55.3\%F_{TU}$)	0.0278	13.076	-	-	-	-	Section and photomicrograph
C-64	64-F, M	0.0559	58.37	0	$[0/90]_S$	0.00910	-	47.10 ($53.9\%F_{TU}$)	68.46 ($78.3\%F_{TU}$)	0.0385	11.64	-	-	-	-	Section and photomicrograph
C-63	63-H, R	0.0560	58.77	0.02	$[0/90]_S$	0.0090	56.336	49.854 ($64.2\%F_{TU}$)	64.523 ($83.05\%F_{TU}$)	0.0413	11.924	-	-	-	-	Section and photomicrograph
C-48 †	5-11-K, L	0.0560	55.45	1.56	$[90/0]_S$	0.00825	-	-	29.10‡	0.0205	12.470	-	0.0230	12.470	-	Section and photomicrograph
									- Initial/Subsequent Compression -							
C-57	57-E, N, W	0.0551	56.61	0.92	$[0/90_2/0]_{3T}$	0.00880	-	-	56.540 ($70.4\%F_{CU}$)	-	9.897	79.00	-	10.224		
C-49	5-5-A	0.0564	61.87	3.39	$[0]_{12T}$	0.00830	-	-	101.200 ($76.1\%F_{CU}$)	-	22.454	119.400	-	22.454		
C-57	57-D, P	0.0551	56.61	0.92	$[0/90_2/0]_{3T}$	0.00880	-	-	56.242 ($70.1\%F_{CU}$)	-	10.505	-	-	-	-	Section and photomicrograph

*S.G. - strain gage

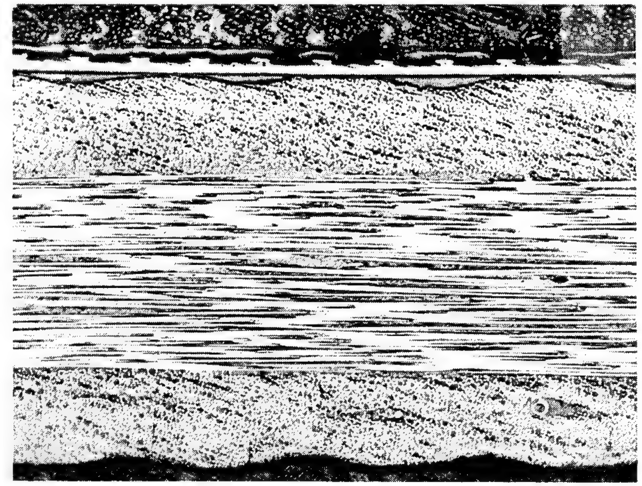
†Specimens loaded twice to same stress before sectioning

‡Not failed

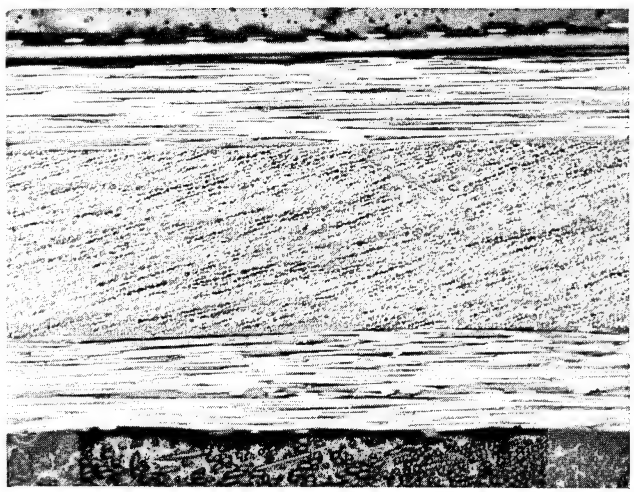
Note: All tension tests run per SwRI 03-401
All compression tests run per SwRI 03-2776-01-3 Dwg. for UT/C Specimen



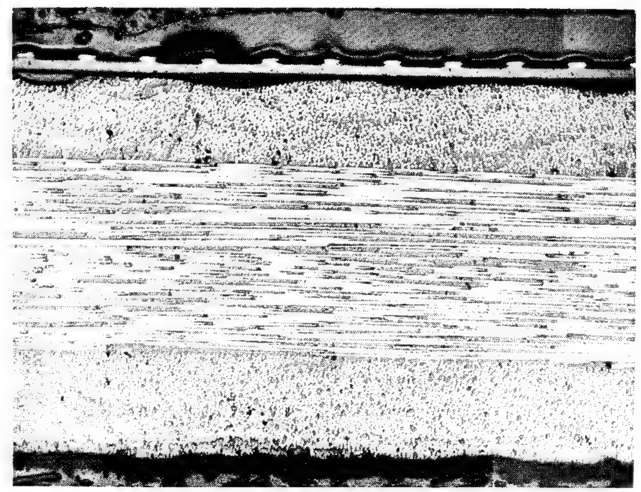
A. Specimen 63-P, Longitudinal Cross-Section
(75X) - 14724



B. Specimen 63-P, Transverse Cross-Section
(75X) - 14719

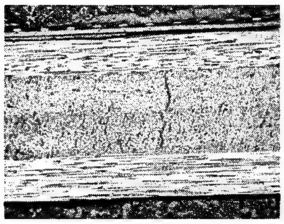


C. Specimen 63-C, Longitudinal Cross-Section
(75X) - 14718

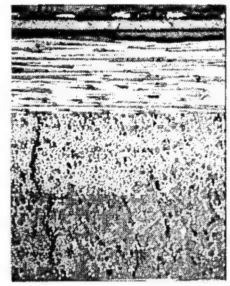


D. Specimen 63-C, Transverse Cross-Section
(75X) - 14723

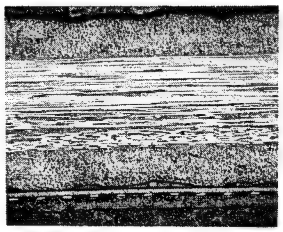
FIGURE 19. PHOTOMICROGRAPHS OF PRELOADED SPECIMENS 63-P AND 63-C



A. Specimen 64-F, Longitudinal Cross-Section (75x) - 14558

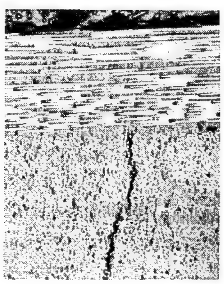


B. Specimen 64-F, Longitudinal Cross-Section (150x) - 14559

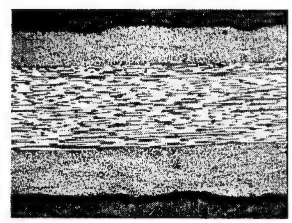


C. Specimen 64-F, Transverse Cross-Section (75x) - 14560

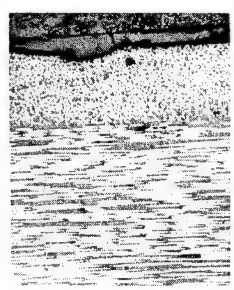
D. Specimen 64-M, Longitudinal Cross-Section (75x) - 14545



E. Specimen 64-M, Longitudinal Cross-Section (150x) - 14546

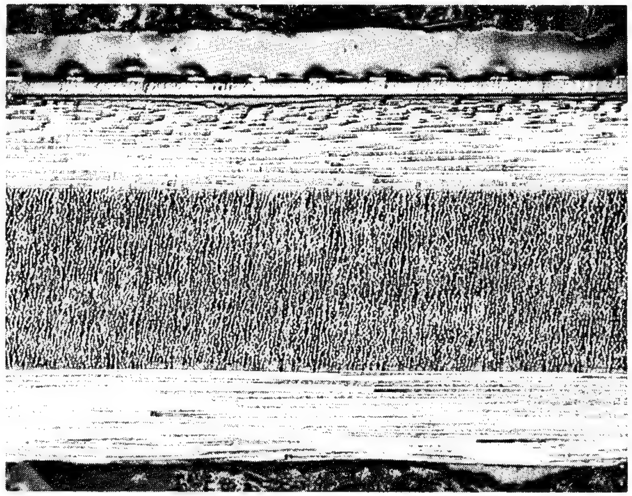


F. Specimen 64-M, Transverse Cross-Section (75x) - 14551

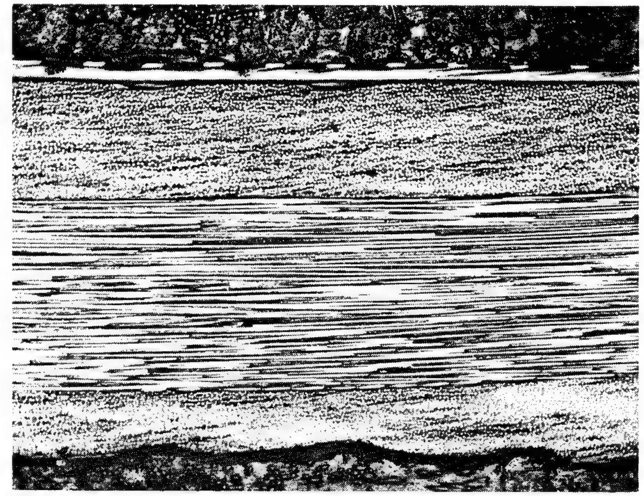


G. Specimen 64-M, Transverse Cross-Section (150x) - 14552

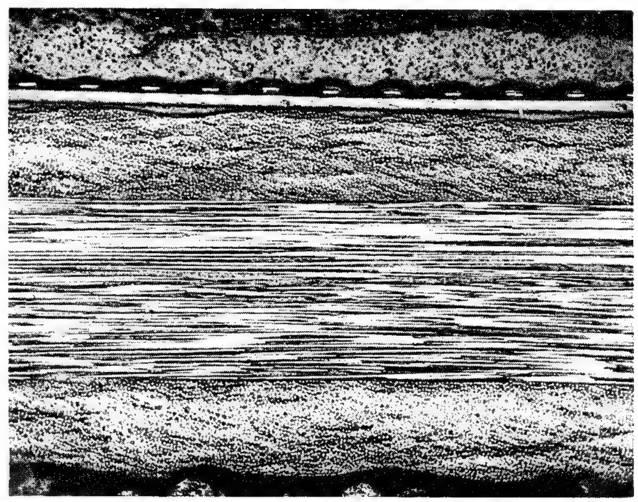
FIGURE 20. PHOTOMICROGRAPHS OF PRELOADED SPECIMENS 64-F AND 64-M



A. Longitudinal Cross-Section (75X) - 14738

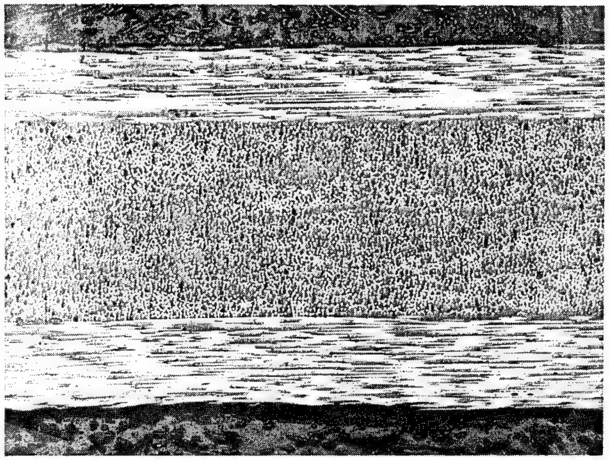


B. Transverse Cross-Section (75X) - 14720

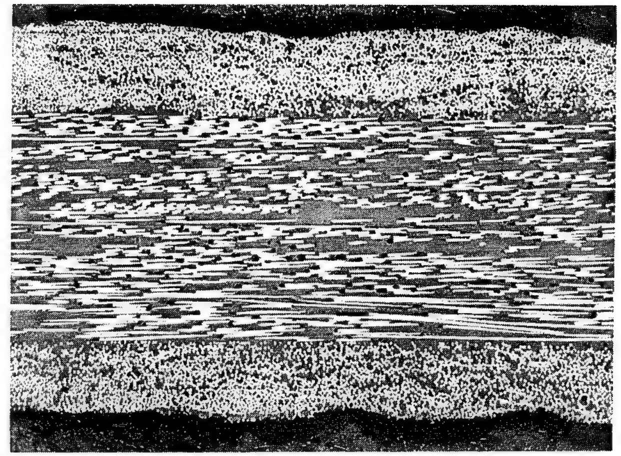


C. Transverse Cross-Section (75X) - 14721

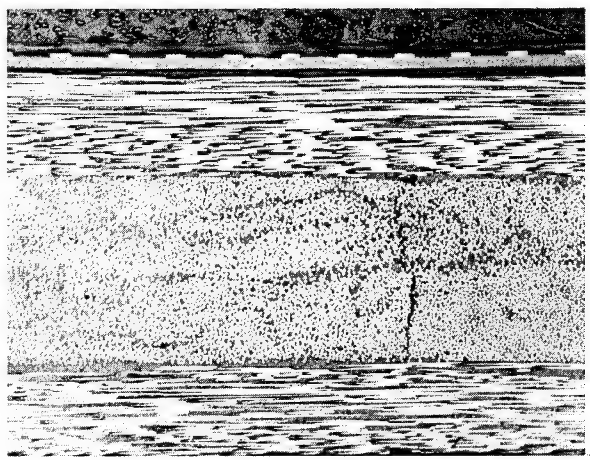
FIGURE 21. PHOTOMICROGRAPHS OF PRELOADED SPECIMEN 63-H



A. Longitudinal Cross-Section (75X)
Before Loading - 14870



B. Transverse Cross-Section (75X)
Before Loading - 14867



C. Longitudinal Cross-Section (75X)
After Loading - 14722

FIGURE 22. PHOTOMICROGRAPHS OF SPECIMEN 63-R

Specimens 5-11-K, -L from $[90/0]_S$ panel C-48 were subjected to an initial/subsequent tension load cycle to 29.1 ksi but not failed. The specimens were then sectioned and studied microscopically. Microphotographs (Fig. 23) of Specimen 5-11-K show large themal stress cracks in both the 0° and 90° plies caused by the panel cure cycle.* The cracks in the 90° plies (Fig. 23, Photos A and B) were opened further by the load cycle. Studying Specimen 5-11-K of Appendix II.3 (Table II.19), it can be seen that the subsequent loading transverse strain was somewhat less than that recorded in the initial loading indicating damage to the 90° plies.† This causes the subsequent loading Poisson's Ratio to be slightly smaller. Specimen 5-11-L was loaded similarly but no cracking was observed in the photomicrographs of Figure 24, and the data in Table II.19 of Appendix II.3 does not show any reduction in subsequent loading transverse strain. Moduli of both specimens were unaffected by the initial/subsequent tension.

Inspection of the ultrasonic records on Panel C-48 from which Specimen 5-11-K, -L were taken show that one end had higher attenuation. This was determined to cover the area where Specimens 5-11-G, -H, -J and -K were taken, with the balance of the panel showing little or no attenuation on the ultrasonic inspection sheet. Such information verifies the thermal stress cracking present which accounts for the low strength and internal damage obtained on these specimens. Data obtained on Specimen 5-11-L, taken from the low attenuation area, was of high quality. However, quality control flexure and interlaminar shear specimens (see Section II) taken from a good area have somewhat low values compared with others of the same orientation. This indicates that even the good areas of the panel (as indicated by ultrasonics) may be of slightly lower than normal quality.

Statistical analysis of the static-monotonic and initial/subsequent loaded tensile specimen data for Panels C-63 and C-64 is shown in Figures 25 through 28. These analyses indicate that there is no significant difference in the data from either panel and that the initial load specimens yielded results on subsequent loading to failure which are statistically similar to the static-monotonically increasing load to failure specimens.‡ These observations are true for both strength and modulus. In addition correlation of strength variation with modulus variation is poor. In fact the strength scatter is substantially greater than the modulus scatter.

Initial/subsequent loaded compression coupons were taken from Panels C-57 and C-49 and are summarized in Table XXXVI and reported in detail in Appendix II.4. Three $[0/90_2/0]_{3T}$ specimens, 57-E, -N, -W, were initially loaded to 70.4% of their ultimate compression strength with subsequent loading to failure. These failure strengths and moduli values showed no degradation from those reported for the static monotonically increasing load data.** The stress-strain curves shown in Appendix II.4 are linear on initial and subsequent loading to failure. Specimens 57-D and P, which were initially loaded to 70.1% F_{CU}, were sectioned and studied microscopically in the center sections. Figure 29 is a typical transverse section photomicrograph of 57-D showing a large crack in one longitudinal ply. This crack which traversed through both matrix and fibers occurred after cure, either as a result of lamination residual stresses or because of the initial compressive loading.†† No such cracking was observed in specimen 57-P of Figure 30 which was also loaded to 70.1% F_{CU} prior to sectioning. Specimen 5-5A from Panel C-49 $[0]_{12T}$ was initially loaded to 76.1% F_{CU} and subsequently loaded to failure, exhibiting no reduction in modulus but a 10% reduction in strength.

---

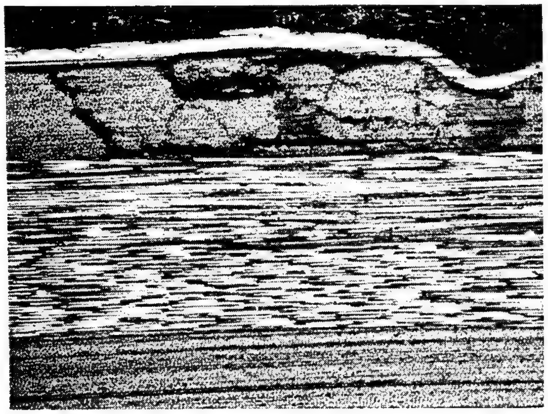
*Actually the cause was a deviation from the standard cure cycle.

†Note that flatwise bending was ±10.9% of nominal strain value.

‡See Table XII of Section III.

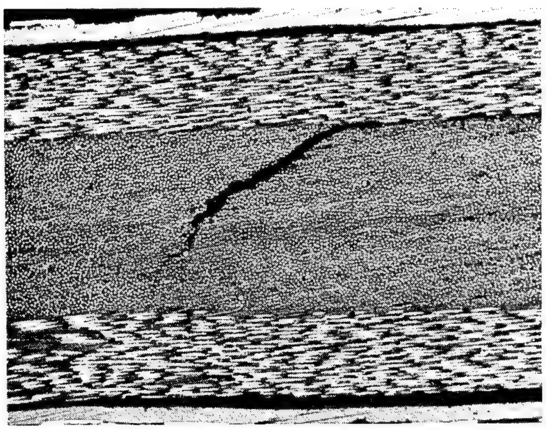
**See Table XIII of Section III.

††The latter cause being most probable because the internal fracture was not picked up on the ultrasonic inspection.

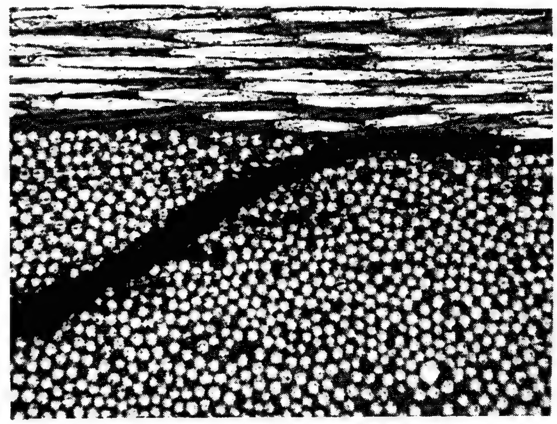


A. Specimen 5-11-K, Longitudinal Cross-Section (75x) - 14239

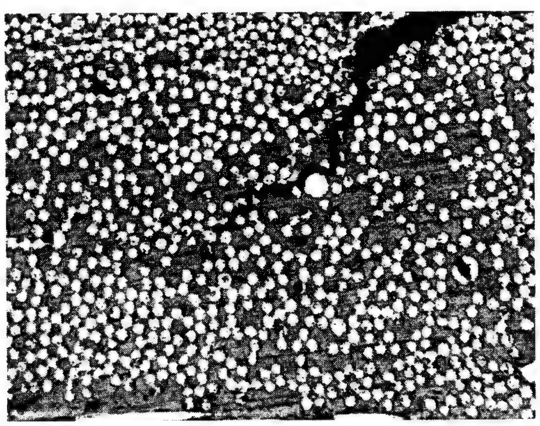
B. Specimen 5-11-K, Longitudinal Cross-Section (150x) - 14240



C. Specimen 5-11-K, Transverse Cross-Section (75x) - 14217

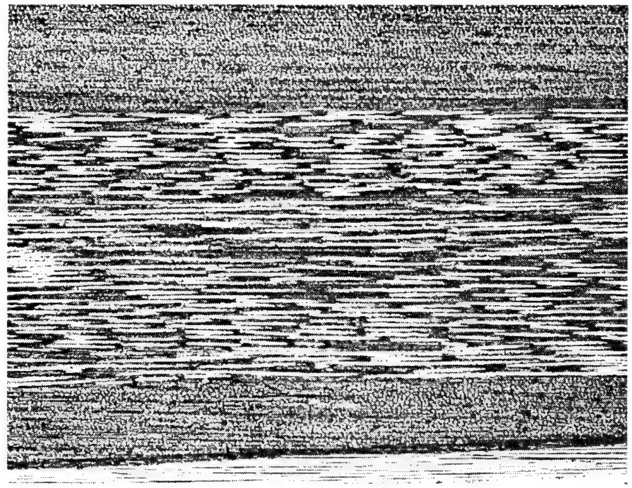


D. Specimen 5-11-K, Transverse Cross-Section (300x) - 14219

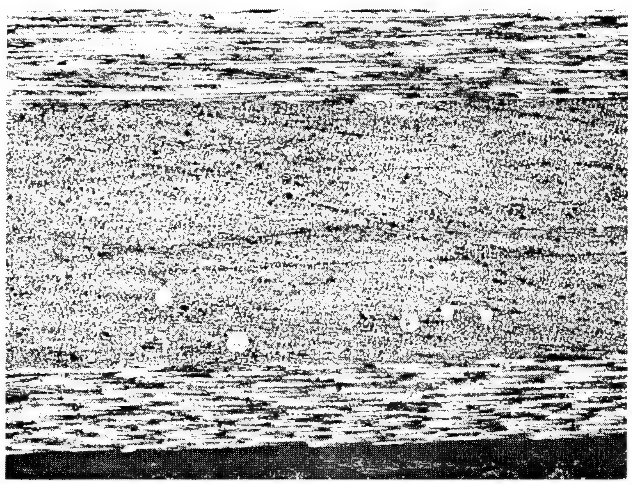


E. Specimen 5-11-K, Transverse Cross-Section (300x) - 14218

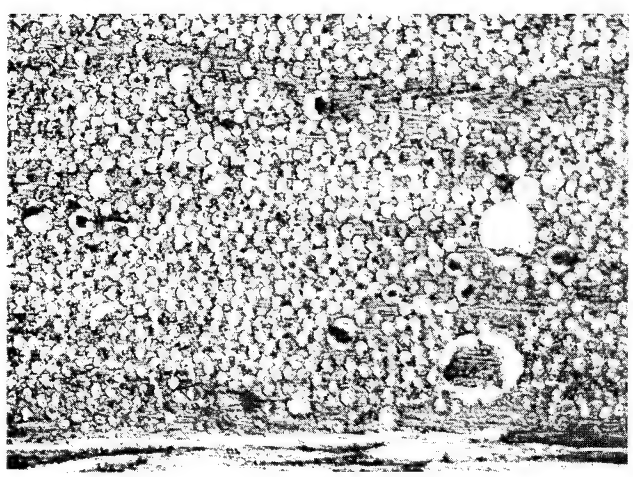
FIGURE 23. PHOTOMICROGRAPHS OF PRELOADED SPECIMEN 5-11-K



A. Specimen 5-11-L, Longitudinal Cross-Section (100x) - 14220



B. Specimen 5-11-L, Transverse Cross-Section (100x) - 14235



C. Specimen 5-11-L, Transverse Cross-Section (300x) - 14236

FIGURE 24. PHOTOMICROGRAPHS OF PRELOADED SPECIMEN 5-11-L

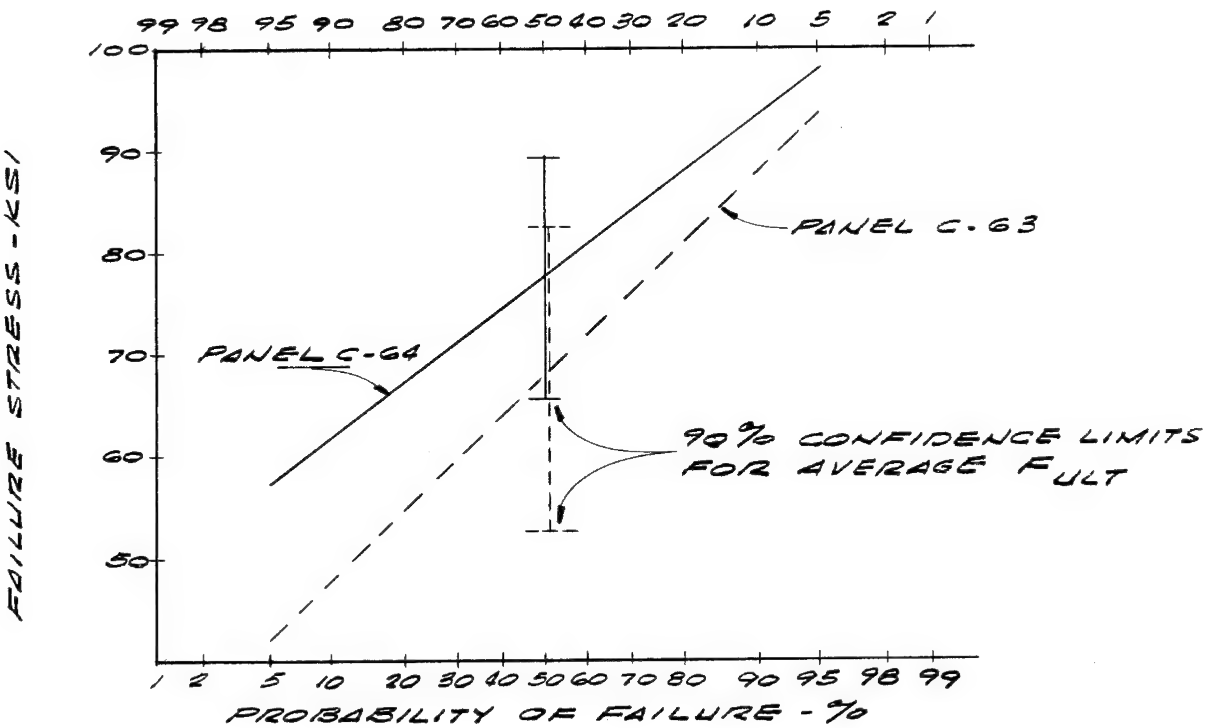


FIGURE 25. ANALYSIS OF STATIC TESTS ON PANELS C-63 AND C-64

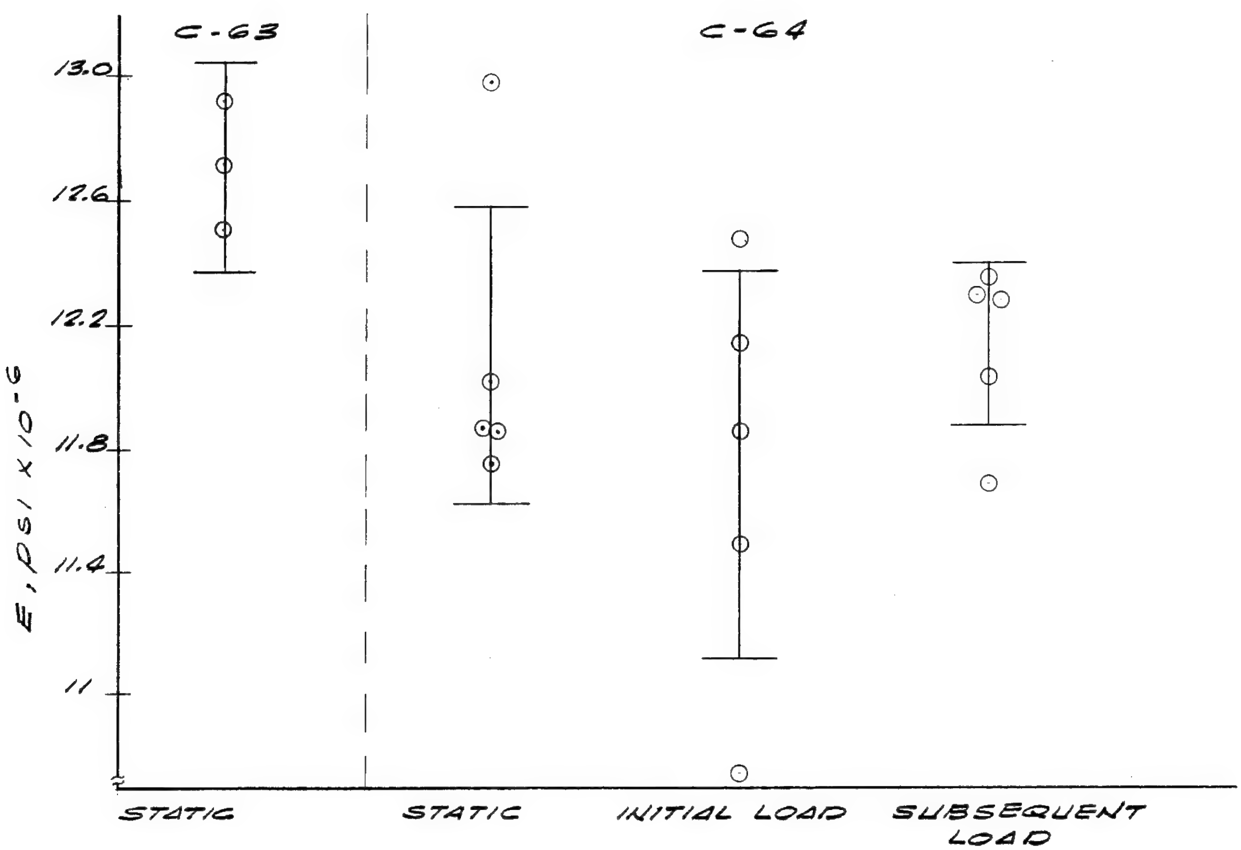


FIGURE 26. MODULI FOR PANELS C-63 AND C-64 (I–90% CONFIDENCE LIMITS FOR AVG. E)

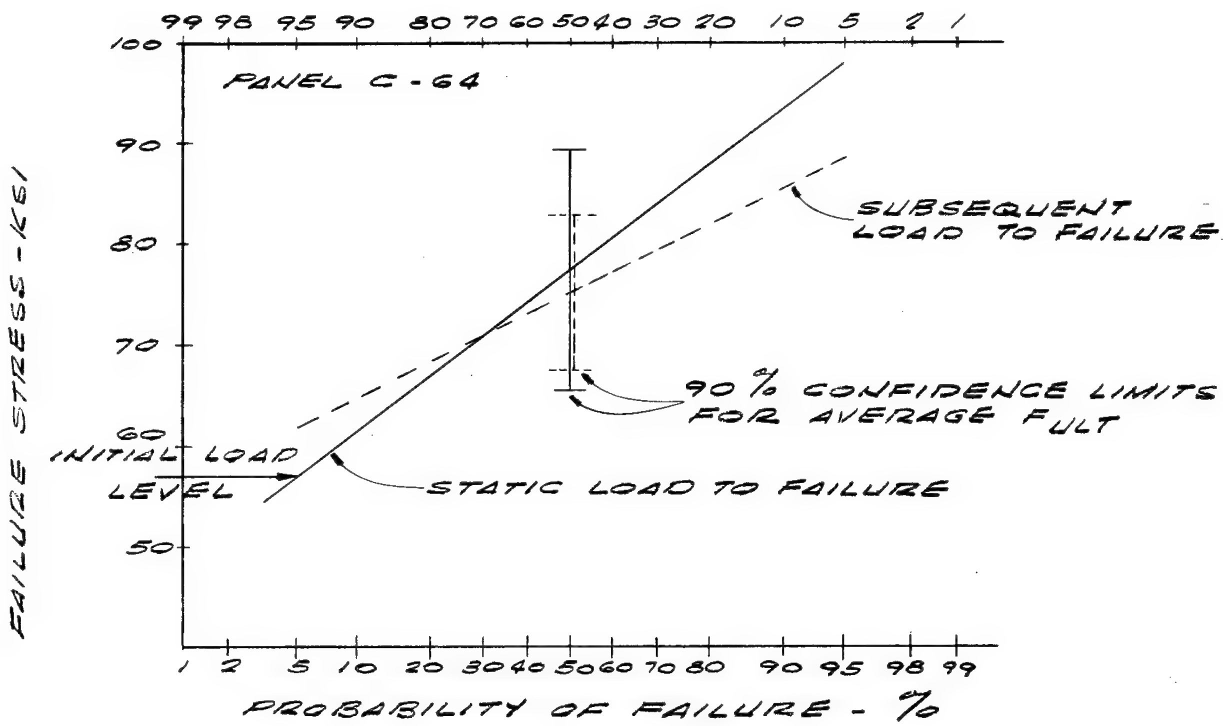


FIGURE 27. INITIAL/SUBSEQUENT LOAD TESTS

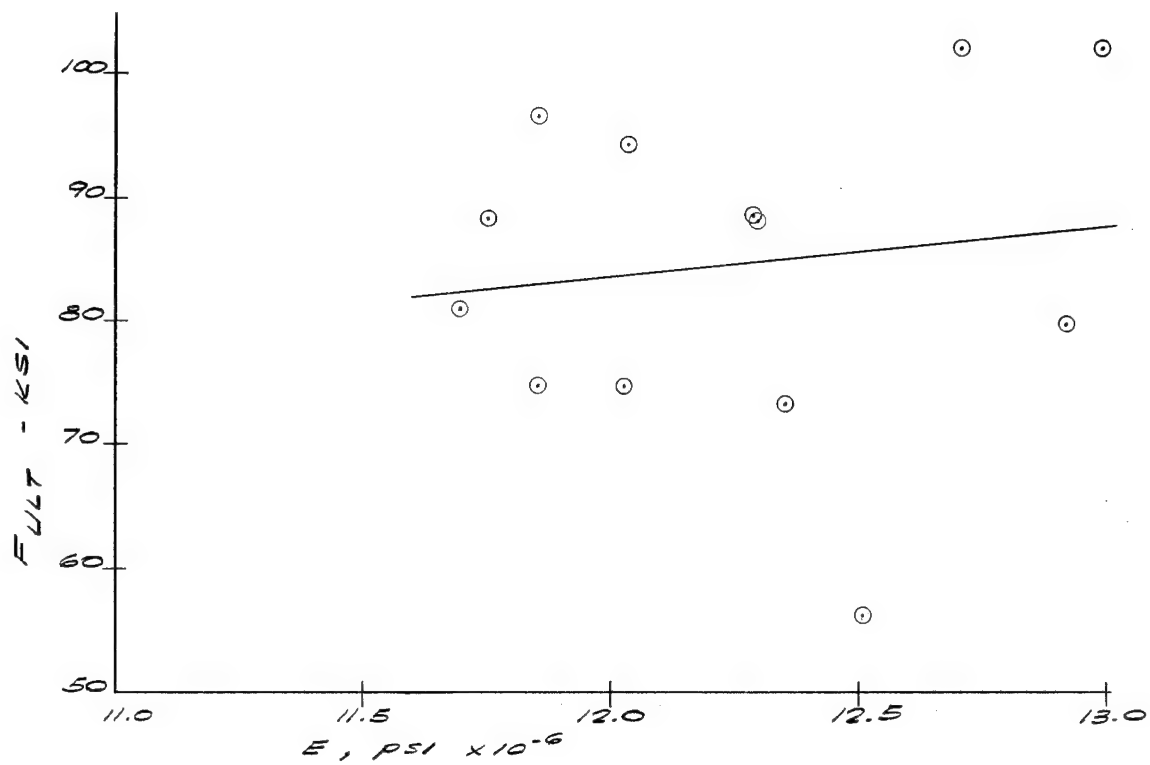
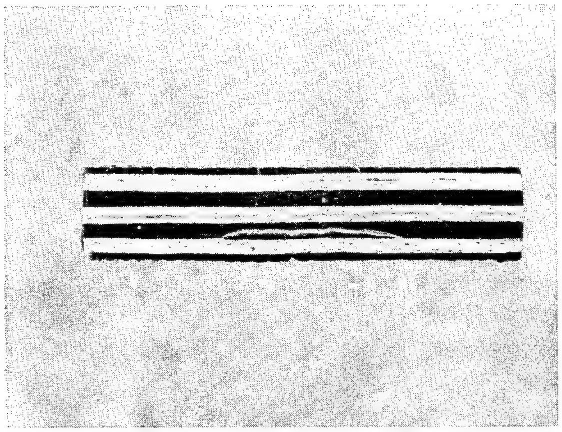
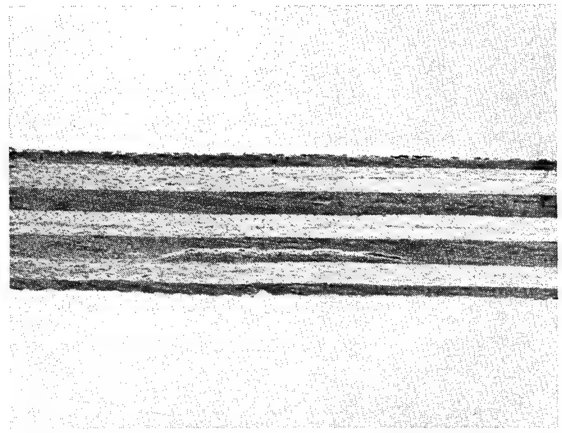


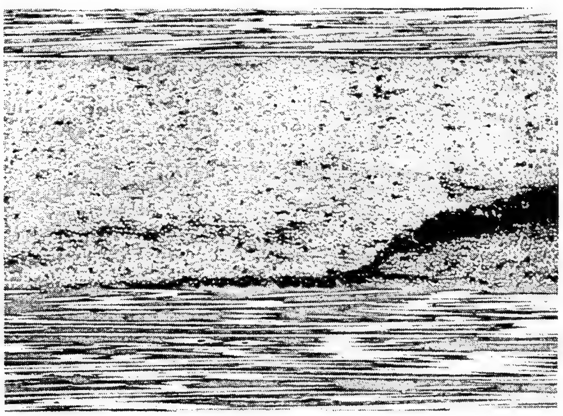
FIGURE 28. MODULUS VS FAILURE STRESS, PANELS C-63 AND C-64
(CORRELATION COEFFICIENT = 0.1319)



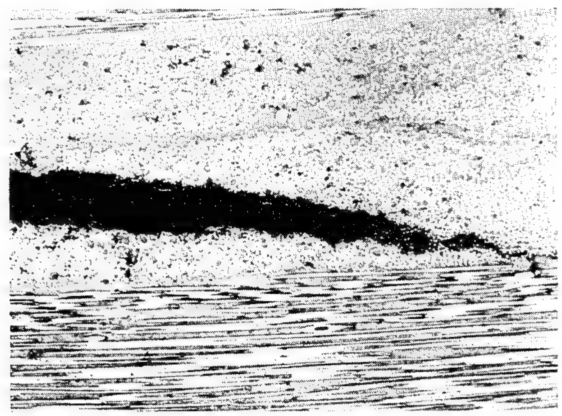
A. Transverse Cross-Section (8X) - 20 Showing Whole Crack



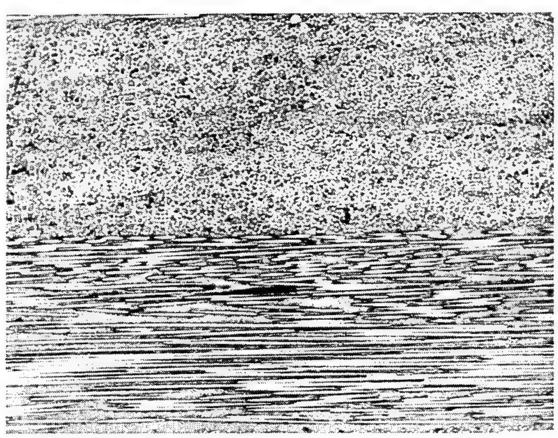
B. Transverse Cross-Section (10X) - 15377 Showing Whole Crack



C. Transverse Cross-Section (100X) - 19 at Left Crack Tip

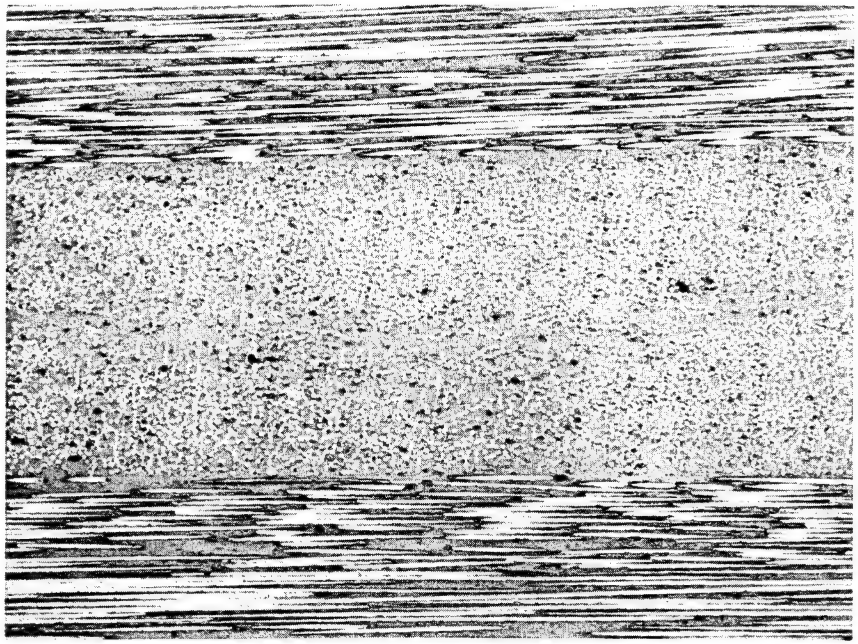


D. Transverse Cross-Section (100X) - 18 at Right Crack Tip

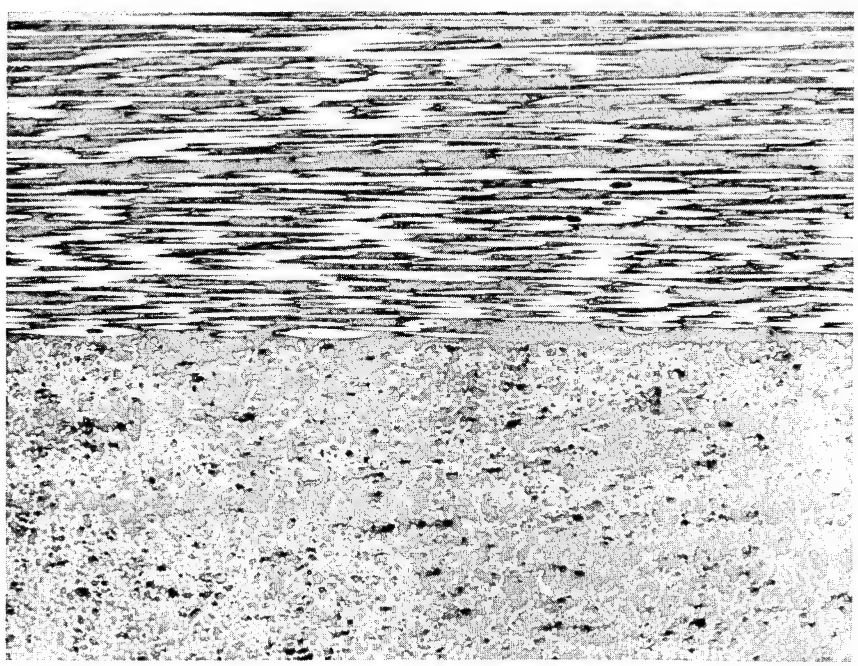


E. Longitudinal Cross-Section (100X) - 17, No Cracks

FIGURE 29. PHOTOMICROGRAPHS OF PRELOADED COMPRESSION SPECIMEN 57-D



A. Longitudinal Cross-Section (100X) - 15, No Cracks



B. Transverse Cross-Section (100X) - 16, No Cracks

FIGURE 30. PHOTOMICROGRAPHS OF PRELOADED COMPRESSION SPECIMEN 57-P

TABLE XXXVII

INITIAL/SUBSEQUENT LOAD TESTS WITH FULLY REVERSED DIRECTION

Panel No.	Specimen Nos.	Density $lbs/in.^3$	% Fiber Vol.	% Void Vol.	Lamination Code	Ply Thick., in.	Initial Loading: Proportional Limit Stress, ksi	Initial Loading: Max. Stress, ksi	Initial Loading: Primary Mod. of Elast., 10^6 psi	Subsequent Loading: Proportional Limit Stress, ksi	Subsequent Loading: Failure or Max. Stress, ksi	Subsequent Loading: Primary Mod. of Elast., 10^6psi	Type Failure	Comments
							- Initial Tension/Subsequent Compression -							
C-57	57-F	0.0551	56.61	0.92	$[0/90_2/0]_{3T}$	0.00880	-	64.80	-	-	56.168	11.718*		
C-57	57-EE, M	0.0551	56.61	0.92	$[0/90_2/0]_{3T}$	0.00880	-	53.318	11.198	-	78.378	10.660*		
C-57	57-GG, G	0.0551	56.61	0.92	$[0/90_2/0]_{3T}$	0.00880	-	53.316	10.050	-	60.471†	9.505*		Photomicrograph specimens
							- Initial Compression/Subsequent Tension -							
C-57	57-A, AA, FF	0.0551	56.61	0.92	$[0/90_2/0]_{3T}$	0.00880	-	56.265	9.476*	-	66.763	10.364		
C-57	57-K, CC	0.0551	56.61	0.92	$[0/90_2/0]_{3T}$	0.00880	-	55.944	10.152*	-	63.823†	11.422		Photomicrograph specimens

*Raw data from Appendix II. 5 was multiplied by 1.09 gage correction factor.

†Specimens not failed

3. INITIAL/SUBSEQUENT TENSION/COMPRESSION AND COMPRESSION/TENSION STATIC LOAD DATA

Five initial/subsequent tension/compression specimens (57-F, -EE, -M, -GG, -G) were tested from Panel C-57 using only longitudinal gages with representative property data presented in Appendix II.5 and all data summarized in Table XXXVII. Specimen 57-F was initially loaded in tension to 93.9% static F_{TU} with subsequent loading to failure in compression occurring at 70.1% static F_{CU}. Specimens 57-EE, -M were initially loaded in tension to an average 77.5% of static F_{TU} with subsequent loading in compression occurring at an average 97.7% of static F_{CU}. A plot of the initial tension stress imposed on these specimens against the subsequent compression failure stress is shown in Figure 31. Static tension data (Table II.7, Appendix II) shows that the tension proportional limit knee ranges from 48.1 to 57.1 ksi. Since Specimens 57-EE, -M were initially loaded in tension to an average of 53.318 ksi it is reasoned that the transverse ply cracking damage threshold had not been reached. So, no damage was induced and subsequent compression tests showed no significant reduction in strength. However, Specimen 57-F was initially loaded to 64.80 ksi in tension, well above the damage stress level range, and it showed a substantial drop in subsequent compression strength (from 80.25 ksi to 56.168 ksi). Specimens 57-G, -GG were initially loaded to an average of 53.316 ksi (77.5% F_{TU}) in tension, subsequently loaded to an average of 60.471 ksi (75.3% F_{CU}) in compression, sectioned and studied microscopically. Transverse strain gages were not used in these tests so only longitudinal strains were measured, however, the initial tension load stress level was at the middle of the critical range of stress levels where the transverse strain proportional limit knees were shown to occur. Figures 32 and 33 show 100X photomicrographs of longitudinal and transverse cross-sections of Specimens 57-GG and 57-G, respectively. Specimen 57-GG* photomicrograph of Figure 32 shows the expected damage in the longitudinal cross-section (90° lamina) as well as some cracking of the 0° lamina in the transverse cross-section. The 90° lamina cracks are the characteristic tension induced cracks running through the matrix and some fibers whereas the 0° lamina cracks† are similar in fracture type to those in the 90° lamina, indicating they may have been induced by the subsequent compression loading causing normal tension (through the thickness) forces. Specimen 57-G‡ photomicrograph (Figure 33) did not show any damage, however, indicating that the loading did not reach high enough levels to induce it. This is about as expected since the maximum tension stress levels were at the middle of the range where damage has been observed and the compression stress levels were below the range where damage had been observed.

Five initial compression/subsequent tension specimens (57-A-, -AA, -FF, -K, -CC) were tested from Panel C-57 with representative property data given in Appendix II.6 and summarized in this subsection in Table XXXVII. The first three specimens (57-A, -AA, -FF) were initially loaded to 56.265 ksi (70.0% F_{CU}) in compression and subsequently loaded in tension to failure at 66.763 ksi (96.5% F_{TU}). The last two specimens (57-K, -CC) were initially loaded to 55.944 ksi (69.7% F_{CU}) in compression and subsequently loaded in tension to 63.823 ksi (92.5% F_{TU}). One specimen (57-CC) failed on the subsequent tension loading, the other did not. Both were subjected to microscopic examinations of longitudinal and transverse cross-sections, shown in Figures 34 and 35. Specimen 57-K which did not fail shows the characteristic tensile cracks in the 90° lamina (longitudinal cross-sections A and B of Figure 34) plus the compression induced tensile cracks in the 0° lamina (transverse cross-section C of Figure 34). Specimen 57-KK was sectioned after failure and the results of the microscopic investigation of longitudinal and transverse cross-sections shown in Figure 35. The longitudinal cross-sections (A through D) show the typical tensile cracks in the 90° lamina with additional delamination and cracking of the 0° layer. Transverse cross-sections (E through G) show the compression induced tensile** cracks in the 0° laminas.

In summary, initial tension stresses imposed on these specimens beyond a certain level resulted in 90° lamina cracking, causing a substantial reduction in subsequent compression strength, i.e., significant damage. For Panel C-57

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*Initial tension = 52.404 ksi, subsequent compression = 63.414 ksi.

†Also observed in initial compression tests which were subsequently sectioned and photomicrographed in Section IV.2.

‡Initial tension = 54.229 ksi, subsequent compression = 57.528 ksi.

**Transverse to thickness.

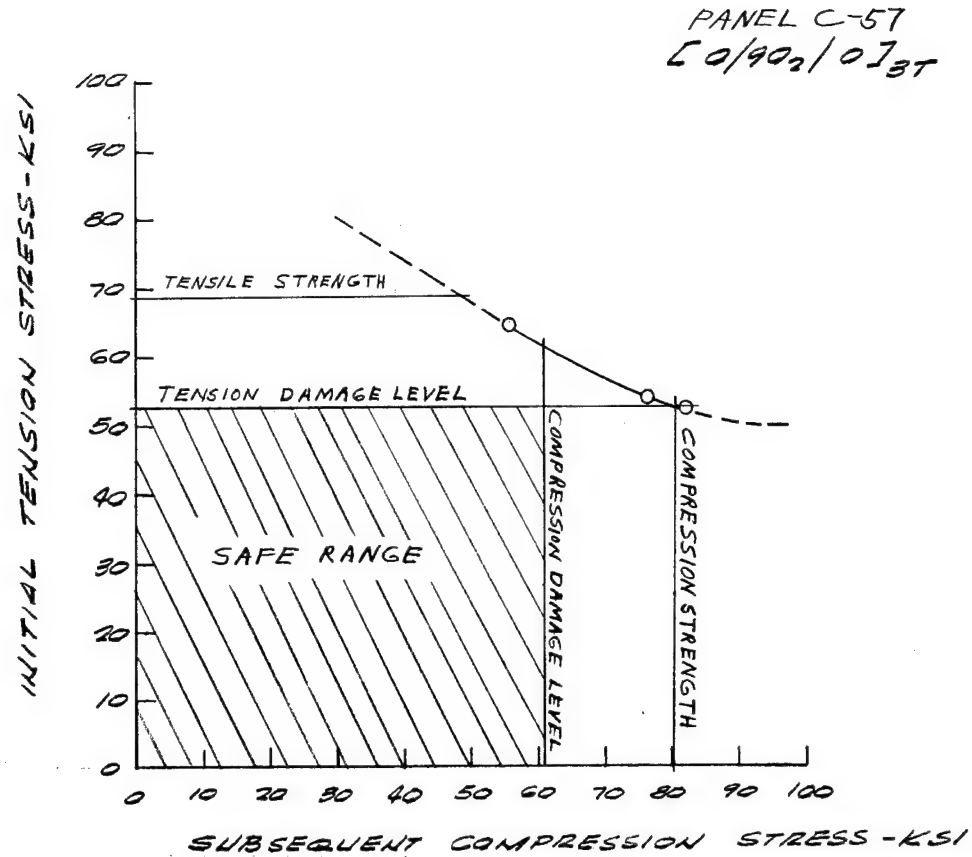


FIGURE 31. INITIAL-TENSION, SUBSEQUENT COMPRESSION CHARACTERISTICS SPECIMENS 57-F, 57-EE, 57-M

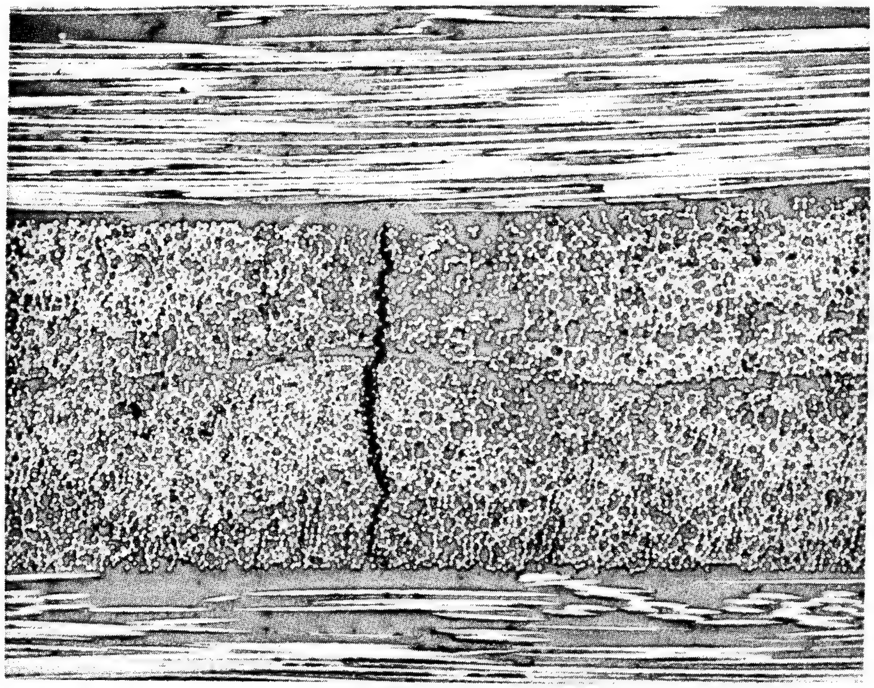
this transverse strain knee (indicating cracking of the 90° lamina) occurred between 69.7% and 82.8% of static ultimate tensile strength.* The experimental relationship of these applied initial tensile stresses to the subsequently applied compression loading strength is shown in Figure 31.

Initial compression loading to approximately 70% F_{CU} had no detrimental effect on the subsequently applied tensile loading strength. However, exceeding this initial compression load level does cause 0° lamina cracking, apparently started by tensile forces in the normal (to the thickness) direction, probably as a result of compression microbuckling of the fibers. Interestingly enough this cracking appears to occur at about the same axial compression strain level at which the $[0]_{12T}$ compression test failures occur. However, the 90° laminas apparently continue to stabilize the cracked 0° laminas until some stabilized strength value is reached, causing diagonal shear failure of the specimen. If this be true the usable 0° lamina compressive strength is about 83% of its tensile strength.

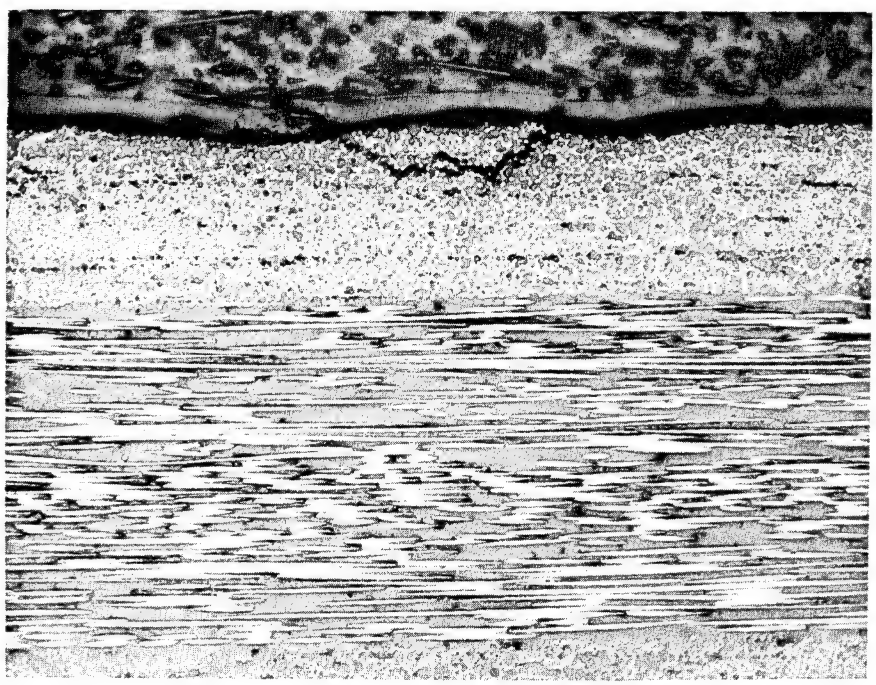
4. TENSILE FATIGUE AND RESIDUAL STRENGTH DATA SUMMARY

Two groups of six straight sided $[0/90_2/0]_{3T}$ tensile fatigue specimens each were tested representing two different 12-ply panels and two slightly different specimen configurations. Detail results of these tests are given in Appendix II.9 including the residual strength stress-strain curves on specimens which did not fail. In graphite/epoxy Specimen Configuration-I the nominal length was 9 inches, and the nominal width was 0.50 inch with 1-inch wide 21-ply fiberglass/epoxy (N-5505 1581) tabs bonded on with a nitrile-epoxy film adhesive (MMM-AF-126-2). Bond area overlap was 1.5 inches giving an L/t of about 25 for the double lap tab/specimen joint with a bonded area of

*76.2% F_{TU} average value.

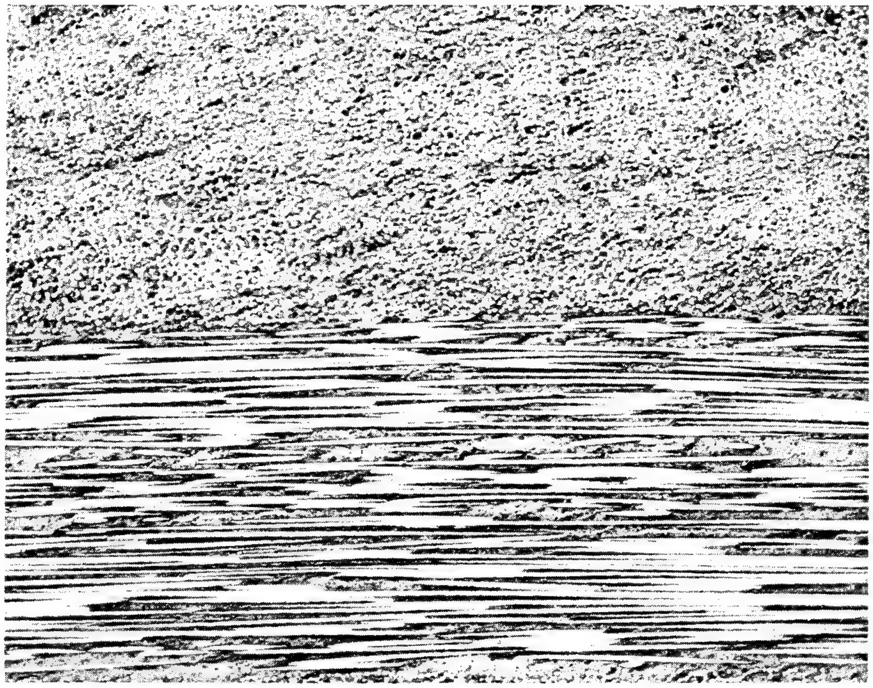


A. Longitudinal Cross-Section, #4

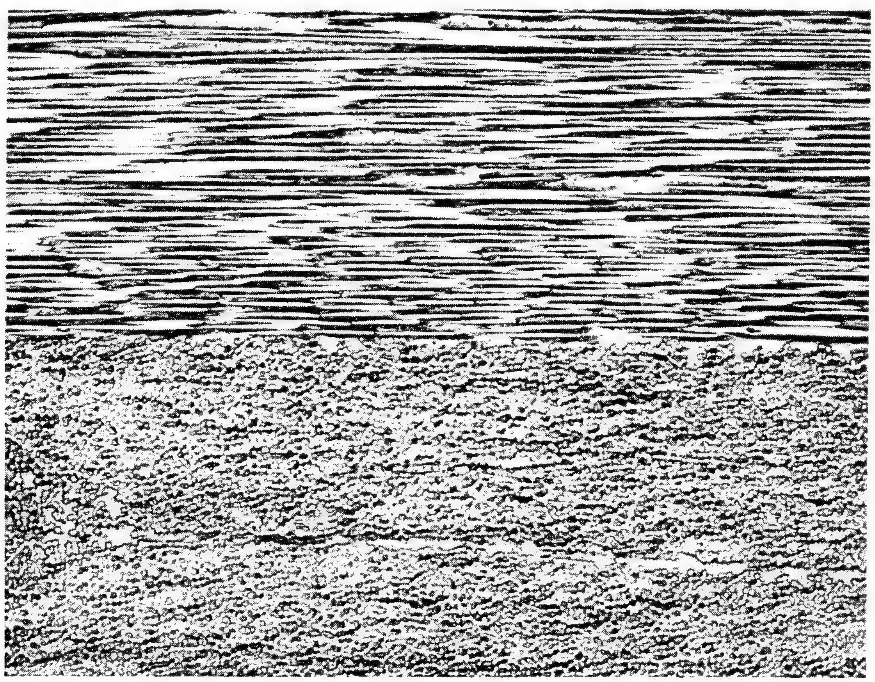


B. Transverse Cross-Section, #6

FIGURE 32. 100X PHOTOMICROGRAPHS OF INITIAL/
SUBSEQUENT TENSION/COMPRESSION
SPECIMEN 57-GG

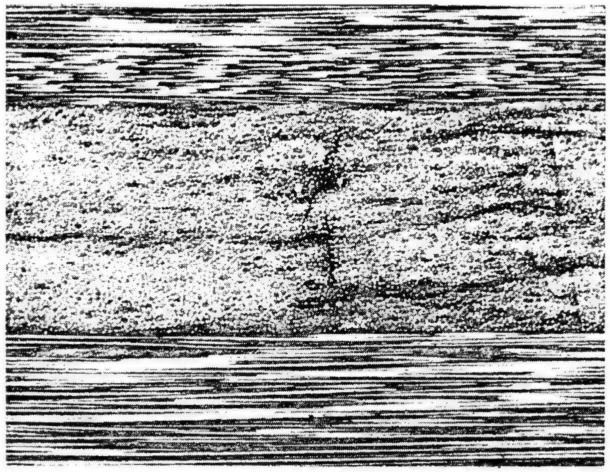


A. Longitudinal Cross-Section, #8

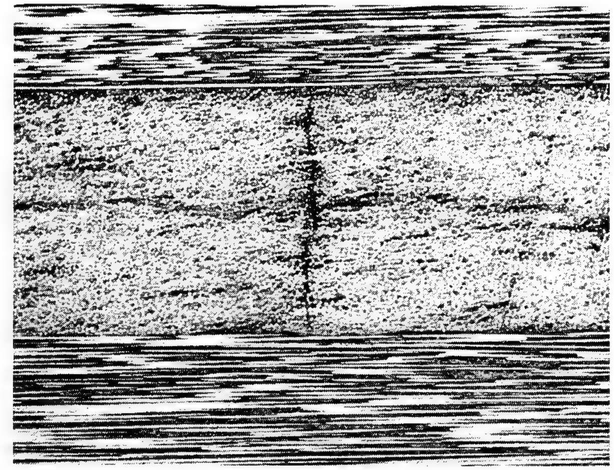


B. Transverse Cross-Section, #7

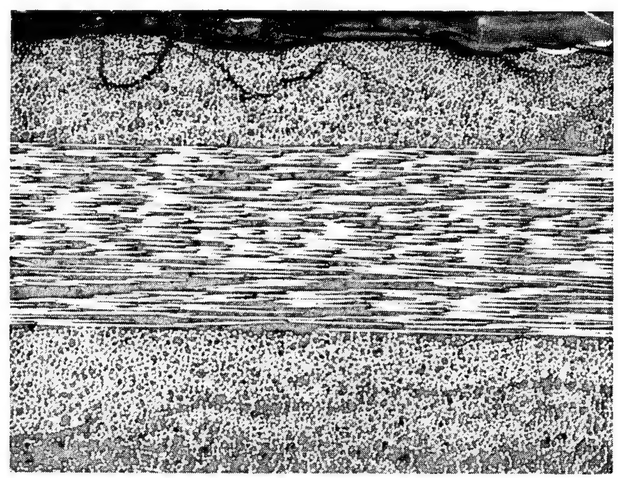
FIGURE 33. 100X PHOTOMICROGRAPHS OF INITIAL/SUBSEQUENT TENSION/COMPRESSION SPECIMEN 57-G



A. Longitudinal Cross-Section, #14

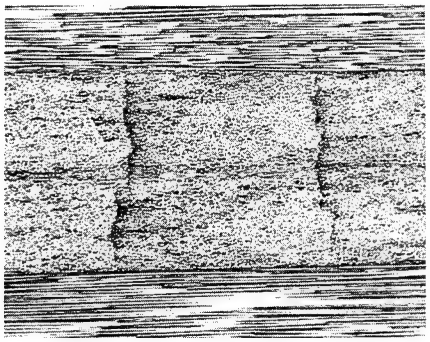


B. Longitudinal Cross-Section, #13

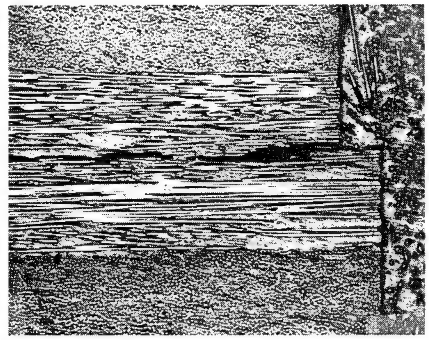


C. Transverse Cross-Section, #5

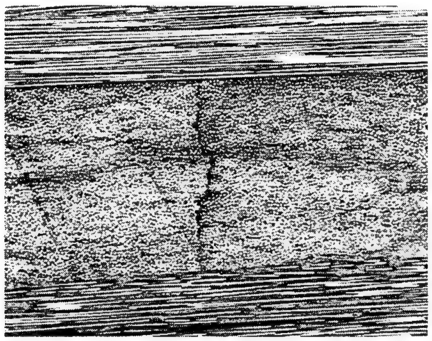
FIGURE 34. PHOTOMICROGRAPHS OF INITIAL COMPRESSION/SUBSEQUENT TENSION SPECIMEN 57-KAT 100X



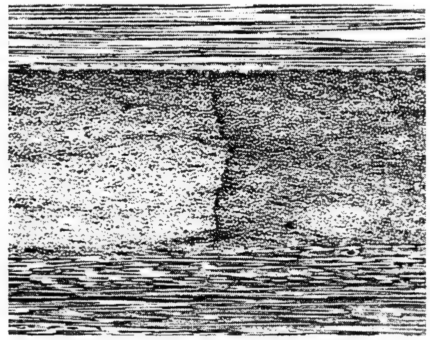
A. Longitudinal Cross-Section, #7



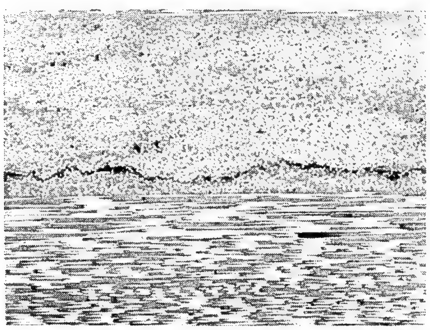
B. Longitudinal Cross-Section, #10



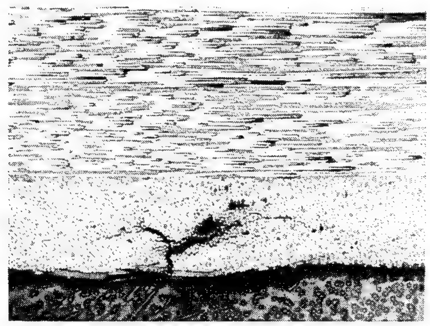
C. Longitudinal Cross-Section, #11



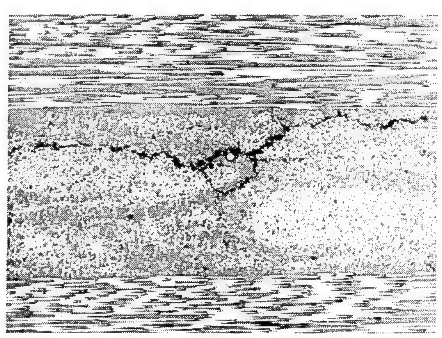
D. Longitudinal Cross-Section, #12



E. Transverse Cross-Section, #1



F. Transverse Cross-Section, #2



Transverse Cross-Section, #3

FIGURE 35. PHOTOMICROGRAPHS OF INITIAL/COMPRESSION SUBSEQUENT TENSION SPECIMEN 57-KK AT 100X

TABLE XXXVIII

TENSILE FATIGUE DATA SUMMARY

Panel No.	Specimen Nos.	Density lbs/in.^{3}	% Fiber Vol.	% Void Vol.	Lamination Code	Ply Thick., in.	Max. Alt. Stress, ksi	Mean Alt. Stress, ksi	Min. Alt. Stress, ksi	No. of Cycles at Failure or Runout 10^6 Cycles	Residual Ten. Strength, ksi	Residual Ten. Mod., 10^6psi	Residual Ten. Poisson's Ratio	Residual Str. Test Stress at Trans. Strain Knee, ksi	Failure Type	Comments
								- Test Group I -								
C-67	67-A, F	0.0552	56.34	0.63	$[0/90_2/0]_{3T}$	0.00860	20.25	10.58	0.965	9.10(R.O.)	63.061	11.389	0.0564	45.200		
C-67	67-C, E	0.0552	56.34	0.63	$[0/90_2/0]_{3T}$	0.00860	59.95	30.50	0.955	0.075(1)	70.226	12.026	0.0748	55.600		
C-67	67-B, D	0.0552	56.34	0.63	$[0/90_2/0]_{3T}$	0.00860	35.95	18.51	1.100	0.0775(1)	60.252	11.586	0.0730	54.100		
								- Test Group II -								
C-57	67-B, C	0.0551	56.61	0.92	$[0/90_2/0]_{3T}$	0.00880	40.12	20.50	0.785	0.042(2)	-	-	-	-	(2)	
C-57	67-D, F	0.0551	56.61	0.92	$[0/90_2/0]_{3T}$	0.00880	20.20	10.30	0.400	10.322(R.O.)	63.705	11.935	0.0658	48.000		
C-57	67-E, G	0.0551	56.61	0.92	$[0/90_2/0]_{3T}$	0.00880	19.82(3)	10.11	0.390	10.438(R.O.)	63.633	11.840	0.0606	55.000		(3)

Notes:
(1) Failed during cycling by delamination of the fiberglass/epoxy load tabs and by bond failure in the nitrile-epoxy adhesive.
(2) Failed in tab adhesive (nitrile/epoxy type) bond with apparently subsequent specimen delamination under tab area. Specimen damaged such that retest not possible.
(3) Specimens preloaded to an average of 25.2 ksi in tension and then fatigue tested as indication.

approximately 3.75 square inches. The fiberglass tabs extended beyond the ends of the specimen another inch for purposes of a 3/8-inch diameter load introduction hole.

Stress analysis of the load introduction system on Configuration -I reveals that the tab/specimen adhesive stress at static tensile specimen failure is 2,120 psi. This value can be compared with average test allowables on similar materials: (1) 3,000 psi taken from Ref (8),* (2) 3,800 psi taken from page 313 of Ref (9),† and (3) 8,510 psi interlaminar shear strength (Ref 3).‡ It is obvious that the static strength is sufficient and this is further proven by the fact that all static and initial subsequent load tension tests were run with this overlap length without any failures in the tab/specimen bondline. Bearing stress in the fiberglass is 23,600 psi at the static tensile strength of the specimen with a bearing allowable (Ref 3) on a similar material of 64,500 psi ultimate and 24,900 psi at 4% elongation. Net section tension of the tab (through bolt hole) is not critical with stress at 14,200 psi compared with an ultimate tensile strength of 56,720 (Ref 9)** psi. Shear out at 14,200 psi is critical though with an allowable (Ref 3) of 14,500 psi. However, the fatigue loads were not as high as the static ones and no shear out failures occurred during the testing.

For Tab Configuration -II the tab/specimen bondline and interlaminar shear stress was reduced to 1,380 psi at static tensile ultimate for the graphite epoxy specimen by increasing the overlap to 2-1/2 inches (L/t = 25); however, the allowable (Ref 9) is reduced to 2,100 psi. Bolted joint is less critical because width was increased from 1 to 1.5 inches.

The most critical point in analysis for both load introduction configurations was shear out, which did not occur in any of the fatigue tests run. Most failures in fatigue specimen load introduction areas were in the bondline and in interlaminar shear of the tab material with some graphite/epoxy interlaminar failure occurring. Tab/specimen bondline and interlaminar stress would not go above 400 psi (L/t = 25) or 667 psi (L/t = 15) without failure in the fatigue test at less than 10^7 cycles.

Average residual strength of these specimens (after fatigue testing) did not deviate from the average static strength although scatter was increased. It is obvious that introducing the load is a serious problem with fatigue specimens.

The tab bondline problem was discovered to be caused by overage adhesive which did not show up under the static conditions utilized in the specimens. Effects of long term 0°F storage on the B-stage uncured adhesive system was evaluated relative to their cured joint static and fatigue lap shear strength in a separate investigation (Ref 10). For the adhesive system studied, a nitrile-epoxy film, the cured joint static strength dropped a projected 40-50% after 36 months storage of the B-stage uncured material. Fatigue endurance limit strength of the nitrile-epoxy system in a cured bonded joint was less than 10% of its static strength after 24 months storage of the uncured adhesive, while six months of storage showed no joint fatigue failures at endurance limit stresses of over 20% of the static ultimate strength and at stress values of more than twice those at which the 24 month storage adhesive failed.

Table XXXVIII summarizes the fatigue data. Group I (Panel C-67) specimens when tested for residual strength exhibited a transverse strain knee at 70.8 to 84.7% F_{TU} whereas the static stress-strain curves from this panel showed

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*Figure 3, τ_{A-C} curve on $[(0/90)_n/\bar{0}]_T$ S-glass epoxy.

†Figure 140, boron/epoxy $[0/+45/0/-45/\bar{0}]_S$/titanium joint.

‡Page 4-77.

**Table IV of Ref (9).

TABLE XXXIX

INCREMENTAL LOAD TESTING IN TENSION AND COMPRESSION

Panel No.	Specimen Nos.	Density lbs/in.^{3}	% Fiber Vol.	% Void Vol.	Lamination Code	Ply Thick., in.	Increments of Loading, ksi	Failure Increment No.	Ultimate Fail. Strength, ksi	Avg. Incr. Load Exten.* Mod. of Elast., 10^6 psi	Avg. Incr. Load LC/SG† Mod. of Elast., 10^6 psi	Poisson's Ratio	Load Incr. No. for Poisson's Ratio	Type Failure	Comments
									- Incremental Tension Load Tests -						
C-39	5-11-D, E	0.0559	59.70	3.34	$[90/0]_S$	0.00725	8.498	10 & 9	78.735	12.974	-	-	-		Mod. range 15.76-11.55 x 10^6 psi
C-39	5-11-F	0.0559	59.70	3.34	$[90/0]_S$	0.00725	7.781	7‡	54.466‡	-	13.732	-	-		Mod. range 14.15-13.30 x 10^6 psi
C-63	63-B	0.0560	58.77	0.02	$[0/90]_S$	0.00900	7.803	10	77.870	-	12.090	0.040	10		Transverse strain knee at 40 ksi
C-63	63-F	0.0560	58.77	0.02	$[0/90]_S$	0.00900	**	7	80.752	-	12.760	0.0225	7		Transverse strain knee at 46.4 ksi
C-63	63-L	0.0560	58.77	0.02	$[0/90]_S$	0.00900	††	8	91.600	-	11.750	-	-		
C-63	63-M	0.0560	58.77	0.02	$[0/90]_S$	0.00900	9.259	8‡	67.972‡	-	12.547	-	-		
C-63	63-Q	0.0560	58.77	0.02	$[0/90]_S$	0.00900	9.235	8‡	67.972‡	14.060	11.690	-	-		
									- Incremental Compression Load Tests -						
C-40	5-13-B	0.0552	55.71	3.04	$[0/90_2/0]_{3T}$	0.00841	‡‡	7	78.090	-	10.998***	-	-		P.L. on #6 & 7 at 39.0 ksi

*Extensometer

†LC/SG - load cell/strain gage

‡Not failed, subsequent section and photomicrograph

**Loading increments 1 and 2 were 19,172 psi; increments 3, 4, 5 and 6 were 9,586 psi, each

††Loading increments 1 and 2 were 19,098 psi; increments 3, 4, 5, 6 and 7 were 9,549 psi, each

‡‡First loading increment was 19,646 psi; loading increments 2 through 6 were 9,823 psi, each

***Correction factor of 1.09 applied

Note: Loading at each cycle is load increment magnitude x load increment no., except for last or failing load.

no such knee.* Also the residual strength Poisson's ratios were substantially higher than the static test results. Group II exhibited similar residual strength behavior with the transverse strain knee occurring between 69.5 and 79.5% F_{TU} but compared with a static knee at 76% F_{TU}. Poisson's ratios were also substantially higher on Group II residual strength tests than on the static tests. No effect on modulus of elasticity was seen with either group.

5. STATIC INCREMENTAL TENSION OR COMPRESSION LOADING DATA

Specimens loaded in increasing increments to failure are summarized in Table XXXIX covering three $[90/0]_S$ tensile specimens, five $[0/90]_S$ tensile specimens, and one $[0/90_2/0]_{3T}$ compression specimen. The detailed data sheets and representative stress-strain curves on the incrementally loaded tension specimens are given in Appendix II.7 whereas the data on the incrementally loaded compression specimen is given in Appendix II.8.

For the $[90/0]_S$ tensile specimens from Panel C-39, two (5-11-D, -E) showed about the same strength and stiffness as the $[0/90]_S$ materials under static tension loads. No significant reduction was observed in the values on these incrementally loaded specimens when compared with the static tension tests performed on coupons cut from the same panel. Specimen 5-11-F from Panel C-39 was incrementally loaded but not failed and Figure 36 shows photomicrographs of longitudinal and transverse sections of it. Two things stand out in these pictures: (1) the longitudinal cross-section shows the 90° ply transverse (to the thickness) cracks (Figure 36, Photo B), similar to those observed in $[0/90]_S$ tensile specimens and (2) the fiber cross-overs shown in the 90° ply transverse cross-sections (Figure 37, Photo D). Whereas the first observation confirms that 90° ply load induced cracking of cross-ply tensile specimens occurs regardless of whether these plies are on the outside or inside, the second observation may be part of the cause of the large tensile strength and modulus scatter observed on these specimens.

For the $[0/90]_S$ tensile specimens from Panel C-63, three (63D, F, L) were incrementally loaded in tension to failure, showing no significant reduction in strength or modulus compared with the static results. As with the static results, a transverse strain knee was observed at about 50% F_{TU}. No load specimens were taken from various locations in Panel C-63, sectioned and photomicrographed with examples shown in Figure 37. No voids or cracks were found. Figure 38 shows the photomicrographs of Specimens 63-M, -Q after incremental loading but not to failure. These photos show the previously observed 90° ply cracking in the longitudinal cross-section caused by the strain incompatibility of the 0° and 90° layers resulting in a sudden deviation of the transverse surface strain at stresses of approximately 50% F_{TU}. No other damage was evident.

Incrementally loaded compression test specimen 5-13B from Panel C-40 showed no significant reduction in strength or modulus from static results. However, a longitudinal strain proportional limit (P.L.) knee at 39.0 ksi (50% F_{CU}) was observed on Cycle Nos. 6 and 7. Interestingly, there was a 20% reduction in modulus on the secondary portion of the curve on Cycle No. 6 compared to the primary portion (see Figure II.50, Appendix II.8), however, the primary modulus on the final and failing Cycle No. 7 was back to normal, with only a 6-1/2% reduction on the modulus exhibited by the secondary portion of the curve. While the 20% modulus reduction on the secondary portion of Cycle No. 6 is significant it wasn't repeatable on the same specimen one cycle later. The Cycle No. 6 knee may indicate some sort of micromechanical damage such as that observed in Sections III and IV. The relaxation observed on unloading probably caused a redistribution of the load carrying (transmitting) capability allowing such damage as seen on Cycle No. 6 to become less detrimental in the subsequent Cycle No. 7.

In summary neither the $[90/0]_S$ nor the $[0/90]_S$ orientations show significant changes in strength or modulus, after incrementally loading to failure in up to 10 cycles. Some reduction in Poisson's ratio did occur as a result of the 90° ply cracking damage observed in the longitudinal cross-section, occurring when the transverse strain proportional limit knee was reached. For $[0/90_2/0]_{3T}$ compression specimens no significant change in strength or modulus was observed after seven cycles to failure, except that a significant reduction (20%) of the secondary modulus on Cycle No. 6 occurred. While Cycle No. 7 to failure exhibited a knee at the same stress level, its primary modulus was back to the preproportional limit knee cycle average with only a small (6-1/2%) reduction observed in the secondary portion of the curve to failure. This compression specimen knee was probably the result of longitudinal ply microbuckling causing tension cracks as observed in Sections IV.2 and IV.3.

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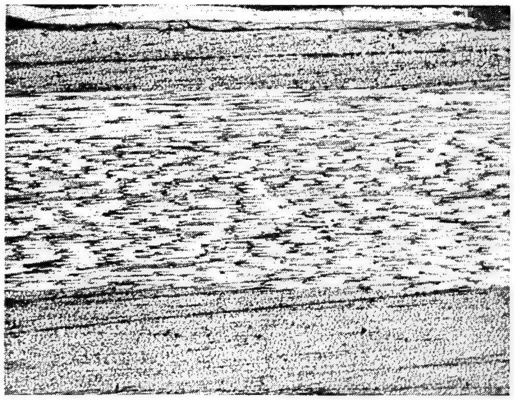
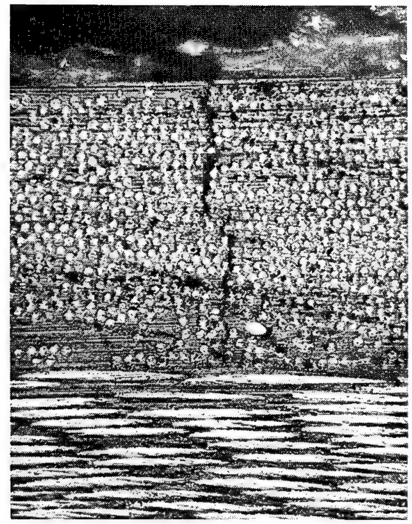
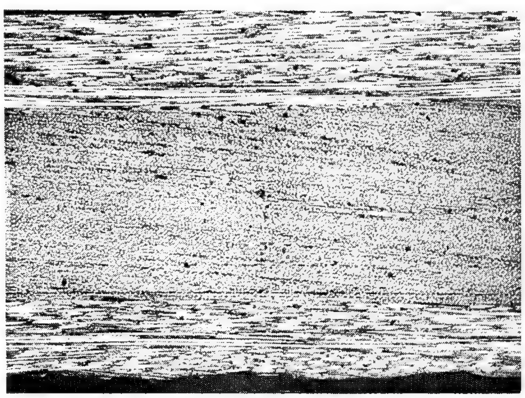
*See Section II and Appendix II.1.



A. Specimen 5-11F, Longitudinal Cross-Section (100x) - 14233



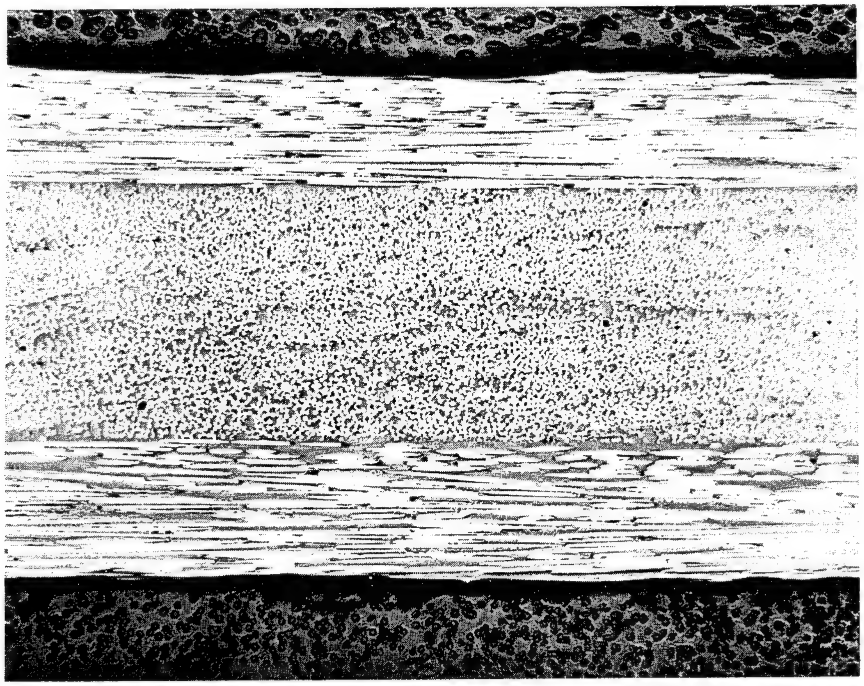
B. Specimen 5-11F, Longitudinal Cross-Section (300x) - 14234



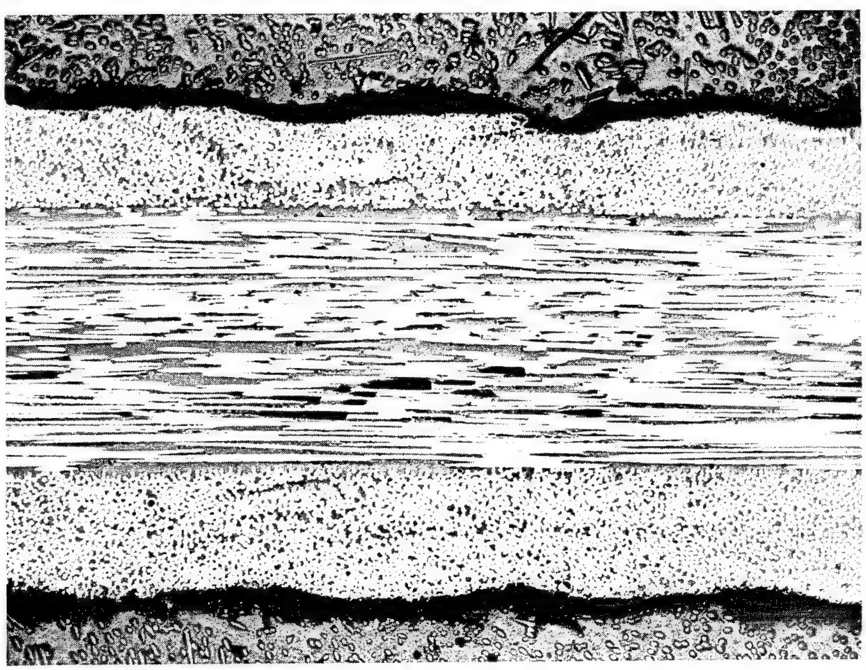
C. Specimen 5-11F, Transverse Cross-Section (100x) - 14237

D. Specimen 5-11F, Transverse Cross-Section (300x) - 14238

FIGURE 36. PHOTOMICROGRAPHS OF INCREMENTALLY LOADED TENSION SPECIMEN 5-11F

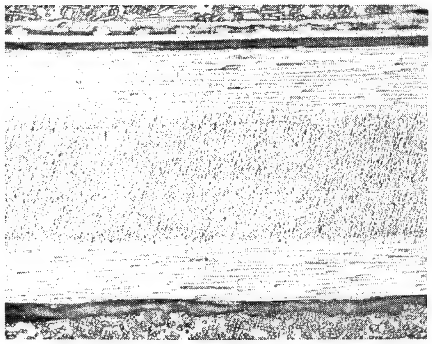


A. Longitudinal Cross-Section, 14871

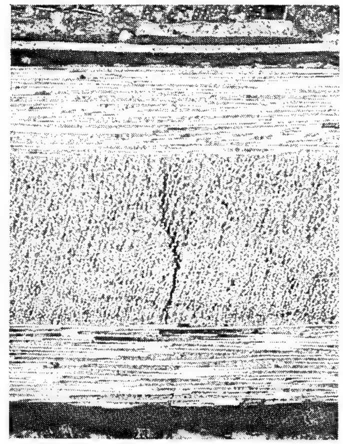


B. Transverse Cross-Section, 14866

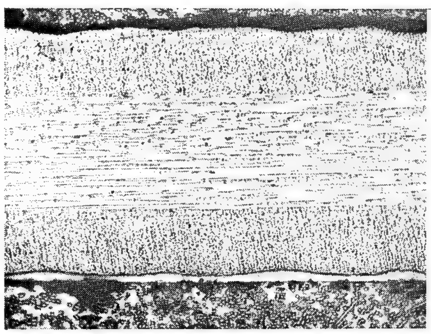
FIGURE 37. NO-LOAD PHOTOMICROGRAPHS OF SPECIMENS FROM C-63 (75X)



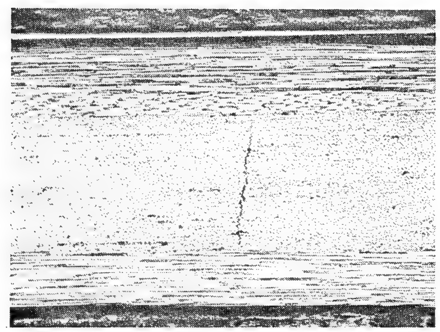
A. Specimen 63-M, Longitudinal Cross-Section (75x) - 14553



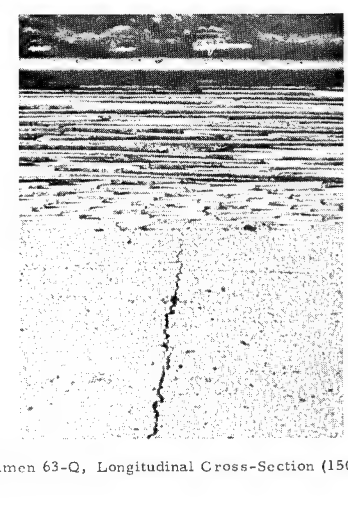
B. Specimen 63-M, Longitudinal Cross-Section (100x) - 14555



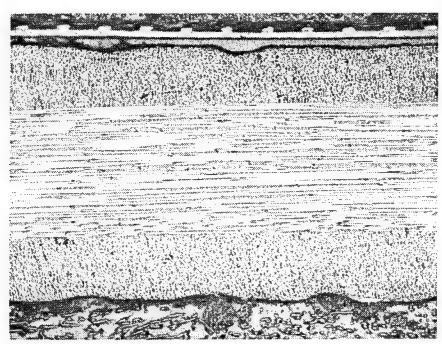
C. Specimen 63-M, Transverse Cross-Section (75x) - 14547



D. Specimen 63-Q, Longitudinal Cross-Section (75x) - 14543



E. Specimen 63-Q, Longitudinal Cross-Section (150x) - 14544



F. Specimen 63-Q, Transverse Cross-Section (75x) - 14549

FIGURE 38. PHOTOMICROGRAPHS OF INCREMENTALLY LOADED TENSION SPECIMENS 63-M AND 63-Q

SECTION V

MATERIAL DESIGN ALLOWABLES AND CRITERIA IMPLICATIONS

1. GENERAL

The purpose of this section is to summarize the reduced and analyzed experimental/analytical data of Sections III and IV in terms of lamina and laminate allowables and to illustrate typical application criteria in using them. Section 2 presents the lamina allowables whereas Section 3 delineates the $[0/90]_c$ and $[90/0]_c$ laminate allowables. Criteria implications are presented in Section 4.

2. LAMINA ALLOWABLES

A review of the $[0]_c$ flat specimen tension and compression data, the $[0]_c$ tube torsion data, and the $[90]_c$ flat specimen tension and compression data for lamina experimental properties was taken from Section III and Appendices II and III and summarized in Table XL, based on acceptable quality panels and tubes. The only anomaly among this data is Panel C-69, $[0]_{18T}$ compression, which gave substantially lower strength values than the $[0]_{12T}$ specimens because the unsupported edge was thicker. Omitting C-69 data, the average experimental and micromechanics calculated values are shown in Table XLI. Correlation of experimental and calculated values is reasonably good except for the $[90]_c$ flat specimen compression modulus and $[0]_c$ tube compression strength analytical values which are 20% and 15% below the experimental ones, respectively. Also, it is obvious that the differences among the F.V.% and V.V.% of the composites would make meaningful direct use in design allowables undesirable. A solution to this problem is to normalize all the pertinent mechanical and physical properties to one F.V.% and V.V.%.

This was done on most of the mechanical properties in Section III, normalizing at 60% F.V. and 1% V.V. Additional pertinent physical properties are density and ply thickness which can be normalized using Figures 39 and 40. These figures were developed from the average physical property data of Table XLI. At the 60/1, F.V./V.V. percentage ratios, the normalized density is 0.05682 lbs/in.^{3} and the ply (or lamina) thickness is 0.00871 in. The normalized experimental and calculated mechanical properties are summarized in Table XLII. All of the values shown in this table were taken from Section III or based on data taken from it. Values which were not normalized in Section III by the micromechanics normalization technique developed therein were normalized for inclusion in Table XLII by the simple expedient of F.V. ratios.* These normalized data now begin to form a reasonable basis for lamina design allowables.

The first attempt at obtaining design allowable strength values was to use a 90% confidence limit (normal distribution) approach to reducing the normalized experimental data. These values are summarized in Table XLIII along with the design allowable values which were obtained from the normalized values using the pertinent related allowable/normalized-experimental value ratio to reduce them. This (F.V. ratio) method was used where only one or two experimental points were available (i.e., not statistically analyzed). The modulus and Poisson's ratio values of Table XLIII are based on average normalized experimental ones, which is customary, although upper and lower 90% confidence limits are available in Section III. It is obvious from the inspection of the stress values in Table XLIII that they are conservative. The reason for this, as mentioned in Section III, is the small number of tests which were run, and in some cases, with substantial strength scatter. A more realistic approach is needed because of the small data sample.

To obtain realistic design allowables from a minimum amount of data requires some judgment as to what would be practical if there were one hundred or more data points available for each property. Since the 90% confidence limits are much wider when a small number of data points are utilized and are widened further by scatter, the 90% lower confidence limit (LCL_{90}) was judged to be a reasonable reduction from the normalized experimental average

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*$[90]_c$ Poisson's ratio values were normalized using the inverse F.V. ratio.

TABLE XL

LAMINA EXPERIMENTAL CHARACTERIZATION DATA SUMMARY
(Ref Tables XII, XIII, XXXIII and Appendices II and III)

Panel No. or Tube No.	Density	%F.V.	%V.V.	Lamination Code	Ply Thickness, in.	σ_{PL} or τ_{PL}, ksi	σ_{ULT} or τ_{ULT}, ksi	E_p or G_p, 10^6 psi	ν
					$[0]_c$ Tension				
C-24	0.0570	65.40	3.57	$[0]_{4T}$	0.00800	-	164.3	28.71	-
C-47	0.0573	64.80	2.88	$[0]_{3T}$	0.00844	-	177.9	23.34	-
					$[90]_c$ Tension				
C-50	0.0563	61.21	3.35	$[90]_{12T}$	0.00858	-	4.923	1.353	0.0215
C-61	0.0546	53.97	0.71	$[90]_{12T}$	0.00991	-	4.360	1.100	0.0248
C-68	0.0551	56.39	0.82	$[90]_{12T}$	0.00946	-	5.620	1.290	0.0200
					$[0]_c$ Torsion				
CT-9	0.0536	47.93	0.41	$[0]_{4T}$	0.0108	1.00	10.500	0.646	-
CT-16	0.0533	47.81	0.45	$[0]_{4T}$	-	1.00	7.570	0.535	-
					$[0]_c$ Compression				
C-49	0.0564	61.87	3.39	$[0]_{12T}$	0.00830	-	133.000	23.849	-
C-69	0.0553	56.88	0	$[0]_{18T}$	0.00920	-	97.867	20.328	-
CT-41	0.0549	55.01	0.73	$[0]_{8T}$	0.00968	70.42	134.400	21.40	0.314
					$[90]_c$ Compression				
C-54	0.0554	56.20	2.89	$[90]_{12T}$	0.00870	10.340	19.620	1.646	-
C-68	0.0551	56.39	0.82	$[90]_{12T}$	0.00946	16.800	26.830	1.210	-

TABLE XLI

SELECTED LAMINA EXPERIMENTAL AND CALCULATED CHARACTERIZATION DATA

Panel or Tube No.	Measured and (Theoretical) Density	%F.V.	%V.V.	Lamination Code	Ply Thickness, in.	Experimental σ_{PL} or τ_{PL}, ksi	Experimental σ_{ULT} or τ_{ULT}, ksi	Experimental E_P or G_P, 10^6 psi	Experimental $\nu_{\ell t}$	Calculated $F_{\ell PL}$ or $S_{\ell PL}$, ksi	Calculated F_U or S_U, ksi	Calculated E_ℓ or G_ℓ, 10^6 psi	Calculated $\nu_{\ell t}$
C-24/C-47	0.05715 (0.059065)	65.100	3.225	$[0]_c$ Tension: $[0]_{3T}$ / $[0]_{4T}$	0.00822	none	192.867	24.78	-	none	205.0	25.550	0.3095
C-50/C-61/ C-68	0.05533 (0.056253)	57.190	1.627	$[90]_c$ Tension: $[90]_{12T}$	0.00931	none	4.968	1.248	0.0221	none	5.227	1.150	-
CT-9/CT-16	0.05345 (0.05383)	47.870	0.540	$[0]_c$ Torsion: $[0]_{4T}$	0.0108	1.00	9.035	0.5905	-	-	-	0.552	-
C-49	0.05640 (0.05833)	61.870	3.390	$[0]_c$ Compression: $[0]_{12T}$	0.00830	none	133.000	23.849	-	none	125.8	24.31	-
CT-41	0.0549	55.01	0.73	$[0]_{8T}$	0.00968	70.42	134.400	21.40	0.314	none	114.252	21.698	0.324
C-54/C-68	0.05525 (0.05630)	56.295	1.855	$[90]_c$ Compression: $[90]_{12T}$	0.00908	13.57	23.225	1.428	-	-	24.35	1.140	-

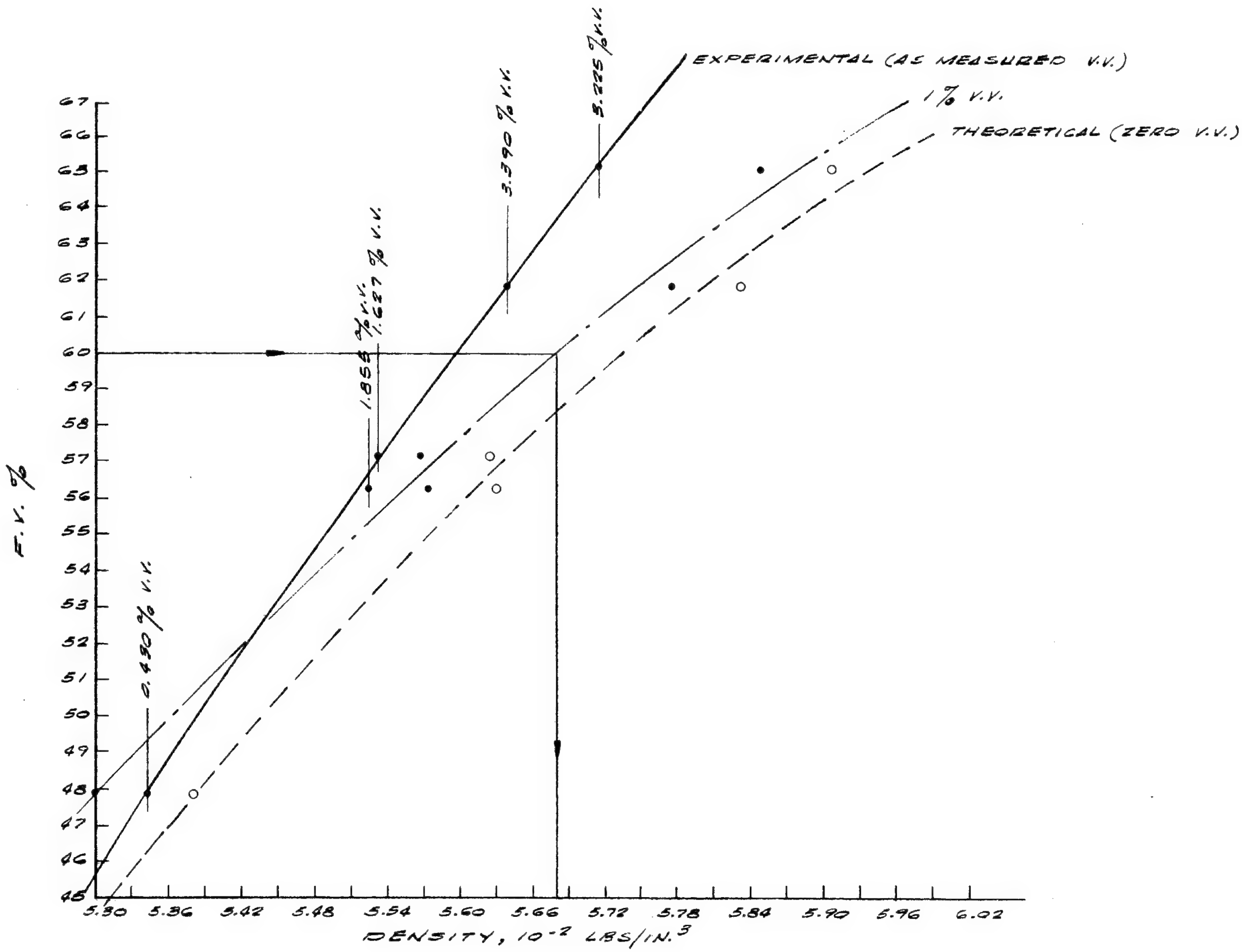


FIGURE 39 PERCENT FIBER VOLUME VS DENSITY FOR $[0]_c$ LAMINATES

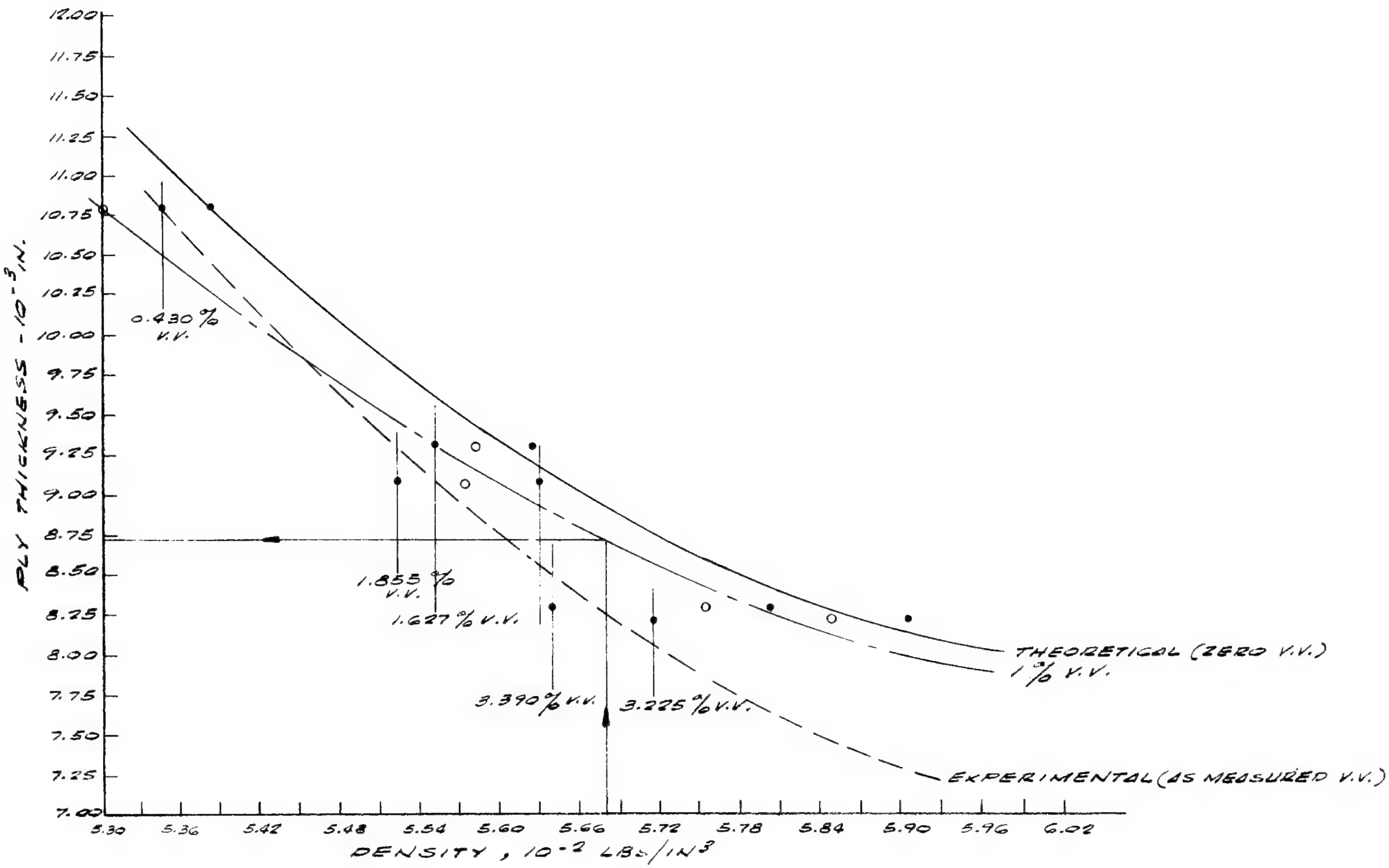


FIGURE 40 PLY THICKNESS VS DENSITY FOR $[0]_c$ LAMINATES

TABLE XLII

NORMALIZED EXPERIMENTAL AND CALCULATED LAMINA CHARACTERIZATION PROPERTIES

F.V. = 60%, V.V. = 1% Density = 0.05682 lbs/in.^{3} Ply Thickness = 0.00871 in.

Panel or Tube No.	Lamination Code	Normalized Experimental: σ_{PL} or τ_{PL}, ksi	σ_{ULT} or τ_{ULT}, ksi	E_P or G_P, 10^6 psi	$\nu_{\ell t}$	Normalized Calculated: F_{PL} or S_{PL}, ksi	F_U or S_U, ksi	E_ℓ or G_ℓ, 10^6 psi	$\nu_{\ell t}$
				$[0]_c$ Tension					
C-24/C-47	$[0]_{3T}/[0]_{4T}$	none	182.720	23.54	-	none	194.500	23.62	0.3205
				$[90]_c$ Tension					
C-50/C-61/C-68	$[90]_{12T}$	none	5.469	1.31	0.0211*	none	5.483	1.19	-
				$[0]_c$ Torsion					
CT-9/CT-16	$[0]_{4T}$	1.470*	11.305*	0.822	-	-	-	0.811	-
				$[0]_c$ Compression					
C-49	$[0]_{12T}$	none	129.950	22.88	†	none	122.947	23.62	-
CT-41	$[0]_{8T}$	50.11	144.62	22.87	0.342*	none	122.947	23.62	0.3205
				$[90]_c$ Compression					
C-54/C-68	$[90]_{12T}$	14.400(1)	24.674	1.40	†	-	25.856	1.19	-

*Normalized experimental value using F.V. ratio normalization.

†Assumed to be the same as the corresponding tension value.

value for realistic design allowable use. Using these stress values (LCL_{90}), Table XLIV was constructed; again using a form:

$$\left[1 - (1/2)\frac{(UCL_{90})_U - (LCL_{90})_L}{\text{Normalized Exp. Ult}}\right] \times (\text{normalized value}) = \text{D.A.} \tag{32}$$

to obtain those design allowables which represented too few data points to calculate reasonable confidence limits. Modulus and Poisson's ratio values are the same as before, normalized average experimental data. The values in this table (XLIV) represent the author's best judgment as to realistic lamina design allowables.

In summary then, Table XLII presents the normalized experimental and calculated lamina properties and Table XLIII presents conservative lamina design allowables whereas Table XLIV gives realistic lamina design allowable values.

3. $[0/90]_c$ AND $[90/0]_c$ LAMINATE ALLOWABLES

A review of the $[0/90]_c$ and $[90/0]_c$ flat specimen and tube data from Section III and Appendices II and III for crossply laminate experimental properties was accomplished to generate the summary shown in Table XLV. These tension, compression, and torsion data are the normalized experimental and calculated values with a F.V. of 60%, a V.V. of 1%, a density of 0.05735 lbs/in.^{3}, and a ply (lamina) thickness of 0.00800 in. Basic mechanical property data are based on panels C-39, -40,-57,-60,-63, and -64 and on Tube CT-43 (torsion). In addition the compression Poisson's ratio was obtained from Tube CT-44. The physical property data was obtained by plotting flat panel data only. In addition to those listed above, panels C-26, -27, -45, -48, -55, and -67 were used in plotting the curves, Figure 41 and 42, necessary to obtain normalized density and ply thickness.

The normalized data in Table XLV was obtained using micro/macromechanics techniques except as noted. Tensile properties utilized both $[0/90]_c$ and $[90/0]_c$ specimen data whereas compression properties used only $[0/90]_c$ data. However, study of panel C-55, $[90/0_2/90]_{3T}$ compression data reveals that the modulus is similar to that of the $[0/90_2/0]_{3T}$ laminate. Proportional limit and ultimate strengths of this panel are low because the specimen load introduction ends were not flat and parallel within the required tolerance.* However it is assumed that the

*See Appendix IV, SwRI Dwg. 03-2776-01-3.

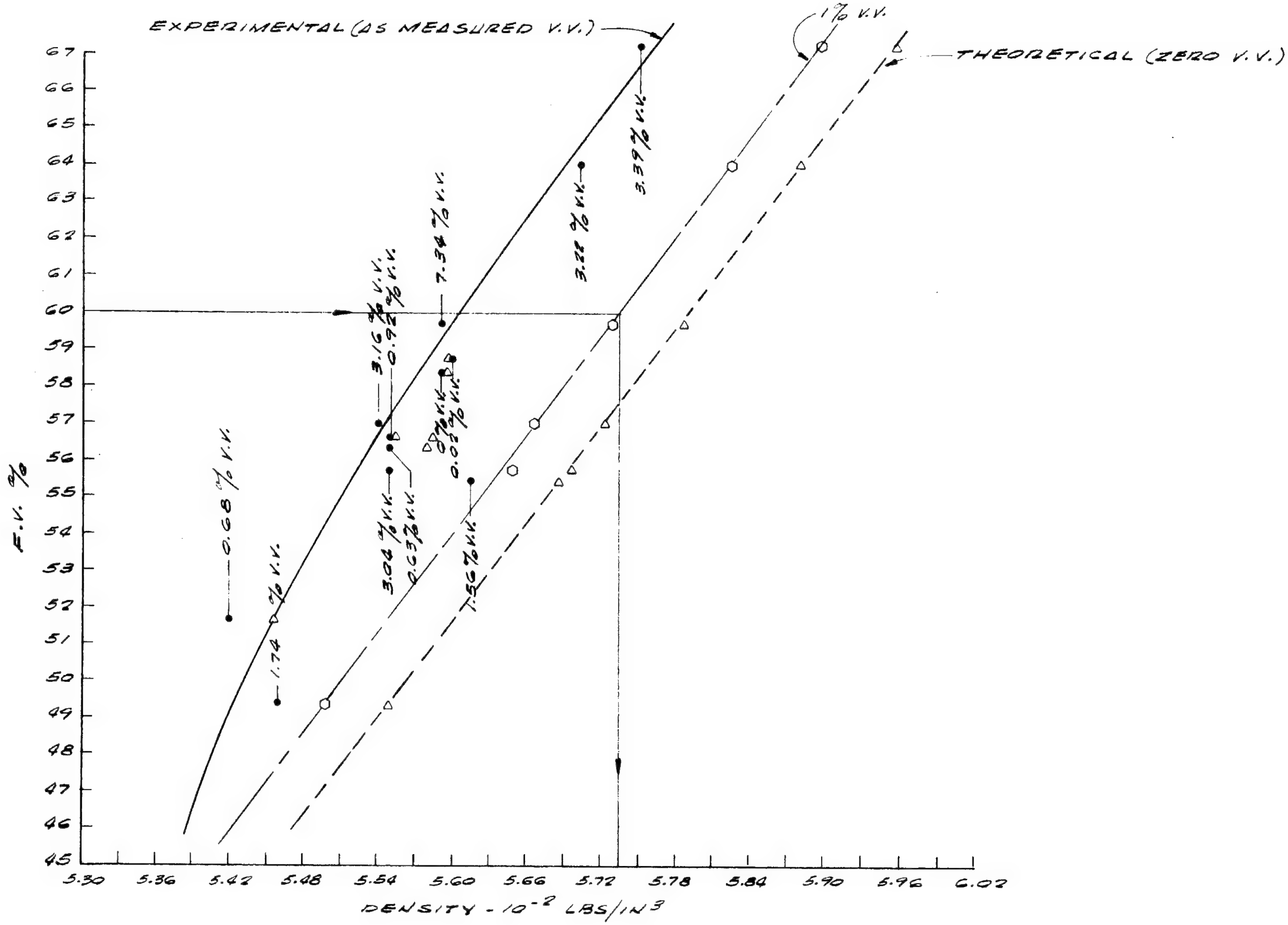


FIGURE 41 PERCENT FIBER VOLUME VS DENSITY FOR $[0/90]_c$ AND $[90/0]_c$ LAMINATES

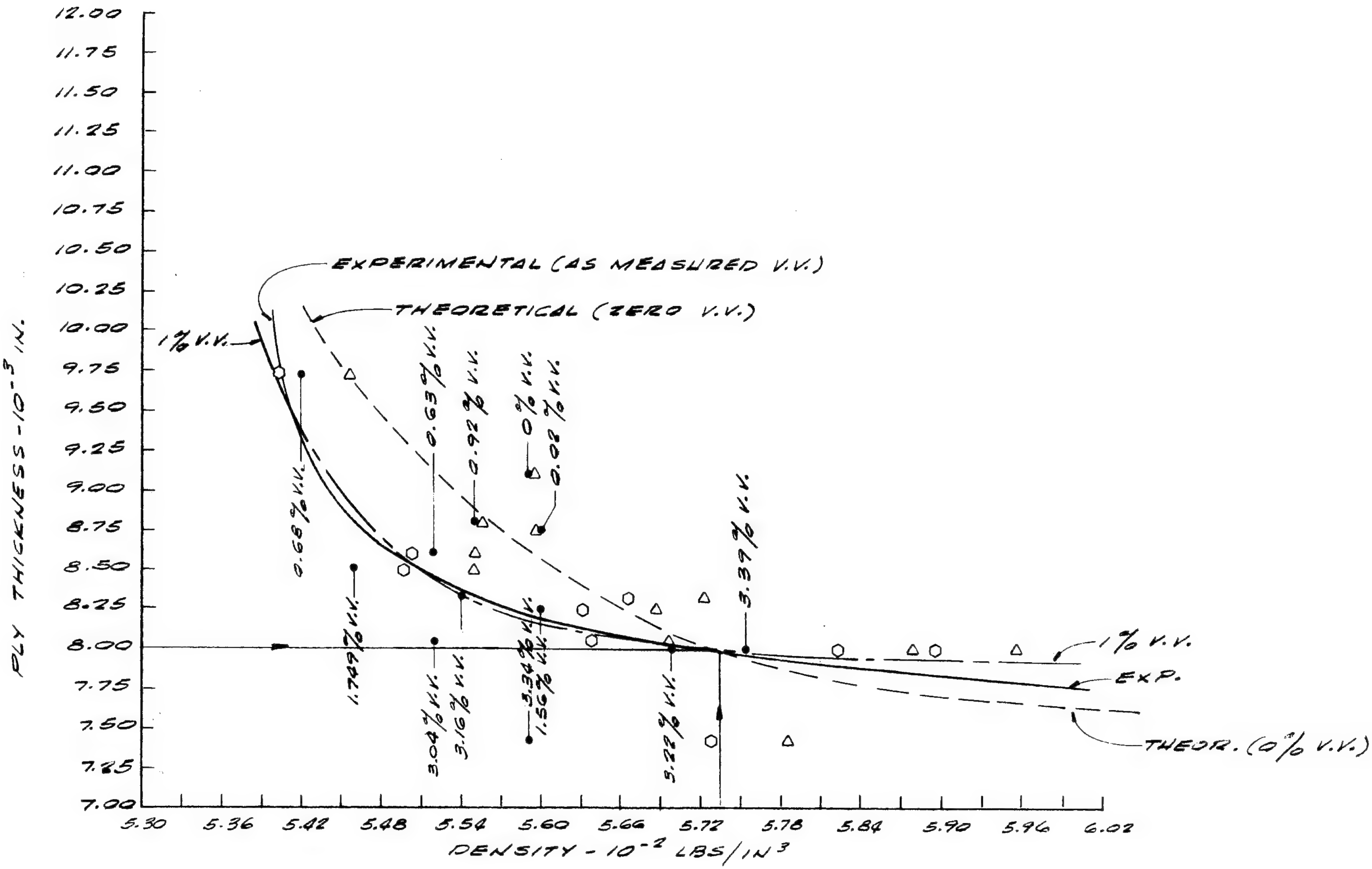


FIGURE 42. PLY THICKNESS VS DENSITY FOR $[0/90]_c$ AND $[90/0]_c$ LAMINATES

TABLE XLIII

CONSERVATIVE DESIGN ALLOWABLES

Normalized Physical Properties

F.V. = 60%, V.V. = 1%	Density = 0.05682 lbs/in.^{3}	Ply Thickness = 0.00871 in.

Lamination Code	σ_{PL} or τ_{PL} ksi	σ_{ULT} or τ_{ULT}, ksi	E_P or G_P, 10^6 psi	$\nu_{\ell t}$
		Tension		
$[0]_c$	none	135.000	23.540	0.3205 *
$[90]_c$	none	3.510	1.310	0.0211 †
		Torsion		
$[0]_c$	0.896	6.900 ‡	0.822	-
		Compression		
$[0]_c$	none	67.140	22.88	0.342 †**
$[90]_c$	7.778 ††	13.360	1.40	**

*Normalized calculated value (micromechanics normalization).

†Normalized experimental value using F.V. ratio normalization.

‡Design allowables based on:

true strength behavior is similar to the $[0/90_2/0]_{3T}$ orientation based on other mechanical behavior characteristics of C-55 compression specimens, as well as the fact that the tensile behavior for these two lamination sequences, representing the same orientation, are approximately the same.

The tensile proportional limits* are based on the transverse strain knee which occurs at 62.0% of the ultimate tensile strength. This knee has been shown (in Section IV) to be caused by the transverse (to the loading direction) plies cracking (as shown in longitudinal cross-section photo-micrographs). Compression proportional limits* are based on the limited study of Section IV that showed damage, in the form of longitudinal ply cracking (as shown in

*This proportional limit is also the significant damage level stress.

TABLE XLIV

REALISTIC DESIGN ALLOWABLES

Normalized Physical Properties

F.V. = 60%, V.V. = 1% Density = 0.05682 lbs/in.^{3} Ply Thickness = 0.00871 in.

Lamination Code	σ_{PL} or τ_{PL}, ksi	σ_{ULT} or τ_{ULT}, ksi	E_P or G_P, 10^6 psi	$\nu_{\ell t}$
		Tension		
$[0]_c$	none	165.260	23.540	0.3205*
$[90]_c$	none	4.660	1.310	0.0211†
		Torsion		
$[0]_c$	1.160‡	8.910‡	0.822	-
		Compression		
$[0]_c$	none	97.220	22.88	0.342†**
$[90]_c$	13.061††	21.950	1.40	**

*Normalized calculated value (micromechanics normalization)

†Normalized experimental value using F.V. ratio normalization

‡Design allowables based on:

$$\tau_{PL} = \left(\tau_{PL_N}\right)\left\{1 - 1/4\left[\left(\frac{\sigma_{tU_U} - \sigma_{tU_L}}{\sigma_{tU_N}}\right)_{[0]_c} + \left(\frac{\sigma_{tU_U} - \sigma_{tU_L}}{\sigma_{tU_N}}\right)_{[90]_c}\right] - 1/4\left[\left(\frac{\sigma_{CU_U} - \sigma_{CU_L}}{\sigma_{CU_N}}\right)_{[0]_c} + \left(\frac{\sigma_{CU_U} - \sigma_{CU_L}}{\sigma_{CU_N}}\right)_{[90]_c}\right]\right\} = \left(\tau_{PL_N}\right) \times 0.790 \quad (30)$$

where τ_{PL_N} is the normalized value as in note 2.

††Design allowable based on:

$$\sigma_{PL} = \left(\sigma_{CPL_N}\right)\left[1 - 1/2\left(\frac{\sigma_{CU_U} - \sigma_{CU_L}}{\sigma_{CU_N}}\right)_{[90]_c}\right] = \left(\sigma_{CPL_N}\right) \times 0.907 \quad (31)$$

**Assumed to be same as corresponding tension value.

Note: All stress values are the 90% lower confidence limits based on micromechanics normalization except as noted. All modulus and Poisson's ratio values are average normalized experimental values.

the transverse cross-section photomicrographs), at approximately 73.7% of ultimate strength. Normalized ultimate compression strength was 10.3% above the ultimate tensile strength whereas the tensile elastic modulus was 21.5% above the compression value. Compression Poisson's ratio (measured on a tube) was 31% higher than the tensile value. Compression proportional limit* was 34.5% above tensile proportional limit.* Normalized calculated tensile values were 31% above and the normalized calculated compression values were 3.8% below the normalized experimental values, but for the tube in torsion calculated values were very conservative. Their experimental strength value was 2.7 times the calculated one and the experimental shear modulus was about 2.6 times the calculated value.

Conservative strength design allowables based on 90% confidence analysis of the normalized data (normal distribution assumed) are given in Table XLVI. Moduli and Poisson's ratio are normalized average values. Normalizing was done by micro/macro-mechanics except as noted. Because of the limited amount of data, and its scatter, a more realistic approach to strength allowables is needed. Such an approach would be to use the 90% lower confidence limit values as the allowables. For limited amounts of data with large scatter this is felt to be justified because, in the author's estimation, it would more nearly duplicate 90% confidence allowables if a large number (say 100) data points were available for analysis. These realistic design allowables along with the average modulus and Poisson's ratio values are given in Table XLVII.

In summary, Table XLV presents the normalized experimental and calculated values for $[0/90]_c$ and $[90/0]_c$ crossply laminates whereas conservative normalized design allowables are given in Table XLVI. Table XLVII presents the realistic normalized design allowables.

4. CRITERIA IMPLICATIONS

a. Background

Based on the exploratory observations made from the experimental data generated there are two significant damage points in $[0/90]_c$ or $[90/0]_c$ laminates loaded axially. Under tensile loading the damage stress level is

*This proportional limit is also the significant damage stress level.

TABLE XLV

NORMALIZED EXPERIMENTAL AND CALCULATED $[0/90]_c$ AND $[90/0]_c$ LAMINATE PROPERTIES

(Ref Tables XXV, XXVI, XXXV and Appendices II and III)

F.V. = 60%, V.V. = 1% Density = 0.05735 lbs/in.^{3}, Ply Thickness = 0.00800 in.

Normalized Experimental				Normalized Calculated			
$^{\sigma}PL_{NE}$ or $^{\tau}PL_{NE}$, ksi	$^{\sigma}ULT_{NE}$ or $^{\tau}ULT_{NE}$, ksi	E_{NE} or G_{NE}, 10^6 psi	ν_{NE}	$^{\sigma}PL_{NC}$ or $^{\tau}PL_{NC}$, ksi	$^{\sigma}ULT_{NC}$ or $^{\tau}ULT_{NC}$, ksi	E_{NC} or G_{NC}, 10^6 psi	ν_{NC}
Tension							
46.050	74.23	13.370	0.0433*	57.50	97.25	12.468	0.0444*
Torsion							
1.176(1)	23.400	1.960	-	-	8.656	0.766	-
Compression							
62.00†	84.07	10.980	0.0568‡*	64.910	81.00**	12.468	0.0444*

*Normalized by use of F.V. ratios.

†From Section IV it was determined that micromechanical damage in the form of the 0° plies cracking occurred on specimens loaded to approximately 73.7% ultimate strength. This cracking would have undoubtedly been picked up by a transverse gage on the specimen, i.e., a proportional limit. The value shown here is 73.7% of the ultimate value.

‡Based on $[0/90_2/0]_{2T}$ tube compression data (CT-44).

**Micromechanics technique used.

Notes: All data normalized using micromechanics except as noted.

TABLE XLVI

CONSERVATIVE NORMALIZED DESIGN ALLOWABLES FOR $[0/90]_c$ AND $[90/0]_c$ LAMINATES

F.V. = 60%, V.V. = 1% Density = 0.05735 lbs/in.^{3} Ply Thickness = 0.00800 in.

σ_{PL_A} or τ_{PL_A}, ksi	σ_{ULT_A} or τ_{ULT_A}, ksi	E_A or G_A, 10^6 psi	ν_A
	Tension		
31.350*	50.400	13.370	0.0433†
	Torsion		
0.947‡	18.800(3)	1.960	-
	Compression		
58.000*	78.680	10.980	0.0568**†

*Calculated as follows: $\frac{\sigma_{PL_{NE}}}{\sigma_{ULT_{NE}}}$ $\sigma_{ULT_A} = \sigma_{PL_A} = 0.62\,\sigma_{ULT_A}$ (for ten.) (32)

$= 0.737\,\sigma_{ULT_A}$ (for comp) (33)

†Normalized by use of F.V. ratios.

‡Calculated as follows: $1/2\ \frac{\sigma_{T_A}}{\sigma_{N_E}} + \frac{\sigma_{C_A}}{\sigma_{C_{NE}}}$ $\tau_{NE} = \tau_A = 0.807\,\tau_{NE}$

**Based on normalized $[0/90_2/0]_{2T}$ tube compression data.

Note: Design allowables stresses are 90% confidence statistical reductions based on the normalized test data unless otherwise noted. Modulus and Poisson's ratio values are normalized average values.

at an average of 62.0 $\binom{+14\%}{-7\%}$ of the ultimate strength and consists of transverse (to the thickness) micromechanical cracking of the 90° laminas running across the specimen width. After initial loading to this damage stress level or higher, subsequent tensile loading results in a reduced Poisson's ratio value whereas subsequent compression loading results in a significant reduction in compressive strength. Tensile fatigue (R = 0.05) specimens failed before runout (10^7 cycles) at maximum alternating stresses at approximately 58% of the static ultimate strength.* Apparently any number of cycles above 5,000 at or above this stress level cause reduced strength, increased Poisson's ratio, and increased proportional limits. Under compressive loading the damage stress level is approximately 74% (±6%) of the ultimate strength and consists of longitudinal micromechanical cracking of the 0° laminas running across the specimen width. After initial loading in compression to the damage stress level or above, subsequent static incremental loading in compression results in a longitudinal strain knee and a secondary modulus significantly below that of the primary modulus. Although not measured, the subsequent compression loading Poisson's ratio would undoubtedly be significantly changed after initial loading to the damage level stress or higher. The tension load damage points were picked up by the identification of transverse (to specimen width and load direction) strain knees or proportional limits occurring on the longitudinal stress-biaxial strain curves generated under static axial loading and verified by photomicrographic techniques.

The longitudinal strain magnitude at which the $[0/90]_c$ and $[90/0]_c$ tensile specimen stress cracking of the 90° plies occurs, roughly corresponds to the $[90]_c$ experimentally measured longitudinal tensile strain† at its ultimate strength. Compression damage level (stress) strain on $[0/90]_c$ and $[90/0]_c$ specimens in the 0° plies corresponds (approximately) to the $[0]_c$ experimentally measured ultimate (stress) strain.‡ Therefore, it appears that using the $[90]_c$ tensile and $[0]_c$ compression experimental ultimate strain levels, the $[0/90]_c$ and $[90/0]_c$ laminate damage level stresses (in tension and compression) can be predicted with reasonable accuracy. In addition it has been found that these respective $[90]_c$ and $[0]_c$ ultimate strengths can be accurately predicted with empirically modified rule of mixture micromechanics theory. Both $[0]_c$ and $[90]_c$ modulus predictions via

*This failure was partially tab/specimen bond failure and partially specimen delamination.

†As measured on $[90]_c$ tensile specimens prepared and tested per SwRI-S3-401, "Test Standard for Fibrous Composite Tensile Specimens," see Appendix I.

‡As measured on $[0]_{12T}$ laminates using the SwRI Universal Tension/Compression Test Method as shown in SwRI Dwg. 03-2776-01-3 in Appendix IV. This does not appear to be the short column $[0]_c$ ultimate strength (which has been estimated to be 20-25% higher based on $[0/90]_c$ compression results reported herein and short column tests reported by AFML).

TABLE XLVII

REALISTIC NORMALIZED DESIGN ALLOWABLES FOR $[0/90]_c$ AND $[90/0]_c$ LAMINATES

F.V. = 60%, V.V. = 1% Density = 0.05735 lbs/in.^{3} Ply Thickness = 0.00800 in.

σ_{PL_A} or τ_{PL_A}, ksi	σ_{ULT_A} or τ_{ULT_A}, ksi	E_A or G_A, 10^6 psi	ν_A
	Tension		
42.000*	67.690	13.470	0.0433†
	Torsion		
1.103‡	21.900(3)	1.960	-
	Compression		
60.200*	81.840	10.980	0.0568**†

*Calculated as follows:

$$\frac{\sigma_{PL_{NE}}}{\sigma_{ULT_{NE}}} \quad \sigma_{ULT_A} = \sigma_{PL_A} = 0.62\, \sigma_{ULT_A} \text{ (ten.)} \quad (34)$$

$$= 0.737\, \sigma_{ULT_A} \text{ (comp.)} \quad (35)$$

†Normalized by use of F.V. ratios.

‡Calculated as follows:

$$1/2 \; \frac{\sigma_{T_A}}{\sigma_{T_{NE}}} + \frac{\sigma_{C_A}}{\sigma_{C_{NE}}} \quad \tau_{NE} = \tau_A = 0.94\, \tau_{NE}$$

**Based on normalized $[0/90_2/0]_{2T}$ tube compression data.

Note: Design allowable stresses are based on the 90% lower confidence limit of the normalized data. Modulus and Poisson's ratio values are normalized average values.

macromechanics are accurate. Since the experimental data indicate the longitudinal tension and compression stress-strain curves are linear to failure, then the ultimate strains can also be predicted accurately for both the $[0]_c$ compression ultimate strength* and the $[90]_c$ tension ultimate strength. Poisson's ratio predictions correlate reasonably well with the experimental data.

Ultimate tensile and compressive strength prediction of laminas can be accomplished by empirically modified micromechanics techniques and, due to the linearity of the stress-strain curves the ultimate strength $[0]_c$ strain can be used to predict $[0/90]_c$ and $[90/0]_c$ laminate ultimate strength (and strain). Thus maximum strain theory can be used to predict both the damage level stress and ultimate strength of $[0/90]_c$ and $[90/0]_c$ laminates in tension and compression. Predictions of shear modulus of $[0]_c$ tubes by empirically modified micromechanics methods have been accurate, however prediction of damage level stresses and/or ultimate strengths in shear have been very conservative (low). The prediction accuracy of $[0/90]_c$ shear modulus and strength is not as accurate. Shear modulus can be predicted by the modified macromechanics techniques but damage level stresses and/or ultimate strengths using maximum strain theory are very conservative (low).

b. Criteria Applications

Using the values given in the previous subsections (2 and 3) in design, along with maximum strain theory as described above, will depend on the specific application and the structural criteria involved. In general, for aircraft structures which are required to withstand ultimate loads which are 1.5 times the design limit loads without failure at least once and withstand design limit loads without permanent set, yielding, or other flight prevention damage to the structure a specified number of times, the following materials criteria could be used safely:

First Criteria—$[0/90]_c$ Laminates under Static Loading

(1) Use the statistically reduced maximum strain theory damage level stresses as allowables for structures subjected to design limit loads.

(2) 1.5 times these damage level stresses would be the allowables to be used with the design ultimate load tension structural stresses (such allowable stresses would be less than the statistically reduced

*Ibid. (‡)

tensile ultimate strength values). However, 1.5 times the damage stress level would be slightly above the statistically reduced compression ultimate strength values and therefore the ultimate strength values would be used as allowables for design ultimate compression load structural stresses.

(3) Average elastic properties would be used with lower confidence values used in deflection critical areas.

Second Criteria—$[0/90]_c$ Laminates under Static Loading

(1) Use a conservative statistical reduction on measured ultimate strength values to obtain allowables to be used with design ultimate stresses.

(2) Check these allowables out by comparing them with a value which is 1.5 times the statistically reduced maximum strain theory damage level stresses; 1.5 times the damage level stresses should always be equal to or greater than the statistically reduced ultimate allowable values or the first criteria would have to be used.

(3) Average elastic properties would be used with lower confidence limit values used in deflection critical areas.

Third Criteria—$[0/90]_c$ Laminates under Static Loading

(1) Use statistically reduced maximum strain theory damage level stresses as allowables for structures subjected to design ultimate loads.

(2) Average or lower confidence limit elastic properties would be used as required.

Of these three, the Third Criteria is judged to be the most conservative with the First and Second ones less conservative. There is some indication that the first two criteria may be unconservative if the structure is fatigue critical or subject to large reversal of loading. This would happen if the loads caused the material's damage level stresses to be exceeded at any time during its useful life.

VI. CONCLUSIONS AND RECOMMENDATIONS

1. GENERAL

The purpose of this section is to present the conclusions, accomplishments, and recommendations for future work needed on graphite/epoxy materials intended for primary structural application to USAF aerospace vehicles. Section 2 presents the Accomplishments and Conclusions whereas Section 3 presents the Recommendations.

2. ACCOMPLISHMENTS AND CONCLUSIONS

The exploratory experimental research and development program reported herein accomplished several noteworthy milestones as follows:

- Developed high quality processing techniques for a new commercially available prepreg (Fiberite HY-E-1317B) utilizing Courtauld's (Hercules) HTS graphite fibers and UCC ERLA-2256 modified epoxy resin.
- Developed a unique method of making high quality small diameter (approximately 1.1 inch O.D.) 12 inch long composite tubes with this graphite/epoxy material.
- Developed the improved experimental evaluation techniques which were necessary to locate, measure, and characterize the micromechanical damage stress levels and determine their significance.
- Established the existence of two significant damage stress levels for $[0/90]_c$ and $[90/0]_c$ laminates.
- Developed micro/macro-mechanical data normalization techniques for reducing such information to a common base for analysis and application.
- Developed material design allowables and criteria implications for $[0/90]_c$ HTS/ERLA-2256 (Fiberite HY-E-1317B) graphite/epoxy composites.

Based on these accomplishments, detailed in the body of the report, the following conclusions can be drawn:

a. Materials and Processes

Prepreg materials received were generally of consistently high quality although aging was rapid even at the 0°F storage. As aging of prepreg material increased more pressure was required during cure to achieve satisfactory resin bleedout (fiber volume fraction) until after approximately 90 days when the bleedout had dropped substantially. At this point increased pressure did not help and panel fiber volumes dropped substantially. Therefore, ninety days is the maximum recommended storage life for this Fiberite HY-E-1317B (HTS/ERLA-2256) graphite/epoxy prepreg when used in flat panels. Tube fabrication presented a different problem in that it was sensitive to the materials' starting solids and volatile content and the flow and gel time and temperature. Flow and gel time reduced with age and the temperature at which it occurred changed. After approximately sixty days 0°F storage flow and gel qualities had been reduced until tube fabrication was all but impossible. Deterioration of these characteristics became noticeable at about 30 days and continued. Therefore, a maximum 45-day prepreg storage life is recommended for use in tube fabrication.

It was found that the material received exhibited reasonably consistent stiffness values but scattered strength values (the fibers controlled this property) even when the highest quality, most consistent processing and testing were used. Quality control flexure (4 point loading) on $[0]_c$ laminates were found to give best results when the span/thickness ratio was 32:1 for longitudinal specimens and 25:1 for transverse specimens. Using these ratios for longitudinal and transverse flexure tests of $[0/90]_c$ laminates, the flexure specimens yielded useful qualitative and quantitative information regarding the panel's mechanical performance. Ultrasonic through-scan inspection also

gave useful qualitative results on voids and delaminations but was not, in most cases, indicative of panel quantitative strength or stiffness when voids were low (<4%) and delaminations or foreign matter were not present.

Processing such that all resin bleed-out was accomplished through the materials thickness to the top and bottom (outside and inside for tubes) was used throughout the program. This allowed the control of fiber volume percent with a minimum of fiber wash (misalignment) occurring as a result of processing. All panels, which were properly processed,* showed little or no evidence of thermally induced residual stresses.

b. Experimental Characterization

Seventy-two flat specimens and twenty-one tubes were tested under static monotonically increasing load conditions in order to characterize the HTS/ERLA-2256 graphite/epoxy composite material at R.T. The forty-eight tension specimens were taken from fourteen different panels whereas the twenty-four compression specimens were taken from nine different panels. Additional specimens from these panels were used in the damage level studies. For normalized experimental data from $[0]_c$ laminates the tensile strength is 41% higher than the compression strength, however, modulus values are about the same. For normalized experimental data from $[90]_c$ laminates the compression strength is higher than the tensile values by 375% while the modulus values are about the same. Normalized experimental data from $[0/90]_c$ and $[90/0]_c$ laminates exhibit about the same values for any given property but compressive strengths are 13% higher than tensile strengths and the tensile moduli are 22% higher than compression values. Partial failure surfaces were experimentally developed for $[0]_c$ and $[0/90]_c$ laminates at the ultimate and damage level stresses. For $[0/90]_c$ laminates it was found that maximum strain theory worked well for prediction of axial and biaxial (excluding planar shear) ultimate strength and damage level stresses. Planar shear calculations for strength and modulus of $[0/90]_c$ laminates were very conservative.

Empirically modified micromechanics equations were developed and used to accurately predict lamina properties which were used in the normalization equations. These equations were developed to realistically normalize the experimental and analytical data to a 60% F.V. and a 1% V.V. Such normalization of data allowed more direct comparison and more accurate design allowables determination. In summary the normalized calculated elastic properties using empirically modified micro/macromechanics compared favorably with the normalized experimental data except for the $[0/90]_c$ planar shear modulus. Normalized predicted strength values using empirically modified micromechanics for laminas and maximum strain theory macromechanics for $[0/90]_c$ laminates compared favorably with the experimental values except for the planar shear strength predictions.

c. Significant Damage Stress Levels

In the 51 flat specimen tests performed for this purpose, two significant damage stress levels were observed in the $[0/90]_c$ laminates under axial loading. In tension the 90° ply, transverse to the thickness cracking, at 62.0% of the ultimate $[0/90]_c$ laminate strength† was found to correspond approximately with the $[90]_c$ lamina strain at its ultimate failure stress. In compression the 0° ply longitudinal cracking, partially across the width of the $[0/90]_c$ laminate specimen, occurs at approximately 74% of the ultimate strength. The $[0/90]_c$ specimen strain level at which this 0° ply significant damage in compression occurs is roughly equal to the $[0]_c$ lamina compressive strain at its experimental ultimate failure stress.‡ The $[0/90]_c$ tensile damage level stress was identified by a knee in the longitudinal stress/transverse strain curve and visually verified by microscopic

*This included uniform heat-up and cool-down during cure in a thermally balanced press and tool which had a maximum temperature variation of 10°F at any given cure cycle temperature.

†The 62% F_{TU} value is the average of both 4-ply and 12-ply panels. The 90° ply damage point on 4-ply specimens was at a lower percent of F_{TU} than on the 12-ply specimens, although the strain levels were approximately the same.

‡As measured on a 12-ply specimen made and tested per SwRI 03-2776-01-3 Dwg. (Appendix IV), which represents the onset of fiber microbuckling; short column compressive strength is estimated to be approximately 20-25% higher.

observation of the resulting 90° ply cracks which constitute significant micromechanical degradation. This $[0/90]_c$ tensile damage shows up (1) in subsequent tensile loading Poisson's ratio values which are lower, (2) in reduced subsequent loading compression strength, and (3) in a tensile fatigue (endurance limit) strength which are less than the damage level stress. The $[0/90]_c$ compression damage level stress was identified by sectioning specimens after they were progressively loaded to higher stresses but not failed. The transverse sections revealed cracking in the 0° plies at approximately the 74% of ultimate strength level. The only property change noticed as a result of this micromechanical damage was when specimens were subjected to periodically increasing incremental compressive loadings to eventual failure. On the first cycle after the damage level stress was reached or exceeded there was a knee in the longitudinal compressive stress/strain curve with knees in each of the succeeding cycle stress/strain curves to failure. The resulting secondary modulus was significantly reduced compared with the primary one. Tube compressive tests on $[0/90]_c$ materials exhibited knees on both the longitudinal and transverse strain curves at stress values slightly above 70% ultimate but at strain levels which were close to the $[0]_c$ lamina experimental strain levels at ultimate failure (as measured herein on flat specimens).

d. Design Allowables

Statistical design allowables (90% confidence limit) were developed but the limited amount of data along with the strength scatter resulted in extremely conservative values. Lower confidence limit (90%) values for strength were judged to be more realistic based on the data generated. Three material design allowables criteria were developed for application use of these materials based on the results of the study. The damage stress level played an important role in all three criteria.

3. RECOMMENDATIONS

Based on the study reported herein it is recommended that:

(a) Additional flat specimen fatigue tests be run on the $[0/90]_c$ orientation.

(b) That two commonly used orientations such as $[\pm 45]_c$ and $[0/\pm 45/0]_c$ be investigated for characterization and damage level study.

(c) That additional $[0/90]_c$ specimens be subjected to subsequent fatigue and creep loading after initial loading to damage level stresses.

(d) That additional $[0/90]_c$ specimens be subjected to environmental exposure (salt spray, humidity) after initial loading to the damage level stress in order to measure the subsequent loading residual strength and stiffness character.

(e) Additional $[0]_c$ and $[90]_c$ lamina property specimens are needed to more fully establish the base properties.

(f) Additional tube data are needed for all combined and uniaxial loading modes for both characterization and damage level testing.

(g) Additional numbers of tests in the same modes as performed herein are needed to better establish a statistical base for strength and stiffness and damage level stresses.

(h) Since the significance and character of the damage level stresses need to be more fully explored, additional studies on the cause and character of this micromechanical fracture phenomena through ultimate strength failure are needed, i.e., a micro-fracture mechanics study of the phenomena.

(i) Damage level stresses and their significance should be determined for all graphite/epoxy materials and their relevance to design allowables established prior to application.

(j) The further study and empirical modification of the micro/macro-mechanical predictive and normalization equations to more accurately predict any graphite/epoxy composites' properties should be developed. More specifically, accurate predictive techniques for planar shear properties are badly needed.

(k) All experimental data should be normalized by micro/macro-mechanics normalization techniques for comparison and design use with statistical fabrication limits determined for fiber and void volume and ply thickness as well as corresponding property ranges.

(l) Additional work is needed on the development of complete failure surfaces for these materials at both the damage level and ultimate stresses utilizing the maximum strain and other theories.

LIST OF REFERENCES

1. Tsai, S. W., "Structural Behavior of Composite Materials," NASA-CR-71, July 1964.

2. Whitney, J. M., "Elastic Moduli of Unidirectional Composites with Anisotropic Filaments," *Journal of Composite Materials,* Vol. 1, 1967.

3. MIL-HDBK-17A, *Plastics for Aerospace Vehicles,* Part 1. Reinforced Plastics, Jan. 1971.

4. Ashton, J. E., Halpin, J. C., and Petit, P. H., **Primer on Composite Materials: Analysis**, published by Technomic, 1969.

5. Chamis, C. C., "Failure Criteria for Filamentary Composites," *Composite Materials Testing and Design*, ASTM STP No. 460, 1969.

6. Calcote, L. R., **The Analysis of Laminated Composite Structures**, Van Nostrand Reinhold, New York, 1969.

7. Waddoups, Max E., "Characterization and Design of Composite Materials," **Composite Materials Workshop**, Tsai, Halpin, Pagano, Technomic Publishing Company, Connecticut, 1968.

8. Grimes, G. C., "Stress Distribution in Adhesive Bonded Lap Joints," January, 1971, SAE Paper 710107.

9. Grimes, G. C., et al, "The Development of Nonlinear Analysis Methods for Bonded Joints in Advanced Filamentary Composite Structures," AFFDL-72-97, Sept. 1972, Draft Final Report, Cn F33615-69-C-1641.

10. Grimes, G. C., "Storage Time Effects on Adhesive Mechanical Properties," U.S. Army Picatinny Arsenal **Symposium on Processing for Adhesive Bonded Structures**, to be presented and distributed in August 1972.

APPENDIX I

SPECIFICATIONS

SwRI-S3-101

GENERAL SPECIFICATION

LAMINATE ORIENTATION CODE

Date: March 19, 1970
Prepared by: G. Wolfe
Approved by: G. Grimes

SwRI-S3-101
GENERAL SPECIFICATION

Laminate Orientation Code

1.0 Purpose

The purpose of this specification is to establish a Standard Laminate Code that will provide the user with a clear, concise, and common notation when dealing with Laminated Composite Materials.

2.0 Applicable Documents

"Structural Design Guide for Advanced Composite Applications," First Edition, Section 1. 5.

3.0 Scope

This specification presents only the sections of the Standard Laminate Code that are applicable to the work being done presently at the Institute. For the complete code and a condensed code, see the document referenced above.

Note: This specification is intended to be used in specifying laminate orientation. It does not imply any preferred laminate design.

4.0 Standard Laminate Code

The Standard Laminate Code is used to describe a specific laminate uniquely. It is most simply defined by the following detailed description of its features.

4.1 Standard Code Elements

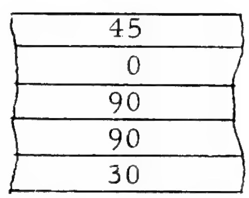
a. Each lamina is denoted by a number representing its orientation in degrees between its filament direction and the X-axis (principal axis).

b. Individual adjacent laminae are separated in the code by a slash, if their angles are different.

c. The laminae are listed in sequence from one laminate face to the other, with brackets indicating the beginning and end of the code.

d. Adjacent laminae of the same angle are denoted by a numerical subscript.

e. A subscript T to the bracket indicates that the total laminate is shown.

Laminate	Code
	$\left[45/0/90_2/30\right]_T$

4.2 Positive and Negative Angles

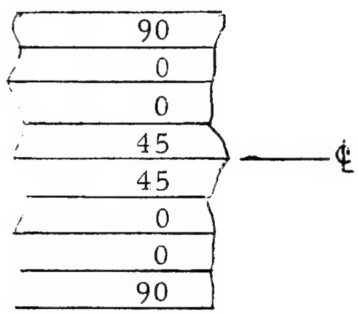
When adjacent laminae are of the same angle but opposite in sign, the appropriate use of + and - signs is employed. Each + or - sign represents one lamina and supersedes the use of the numerical subscript, which is used only when the directions are identical. Positive angles are assumed clockwise:

Laminate	Code
45 0 -60 -60 30	$\left[45/0/-60_2/30\right]_T$
45 -45 -30 +30 0	$\left[\pm 45/\mp 30/0\right]_T$
45 45 -45 -45 0	$\left[45_2/-45_2/0\right]_T$
45 -45 45 -45 0	$\left[(\pm 45)_2/0\right]_T$, or $\left[\pm 45/\pm 45/0\right]_T$
45 -45 -45 45 0	$\left[\pm\mp 45/0\right]_T$
45 -45 -45 45 45 45 -45 -45 45	$\left[+--+++--+45\right]_T$ or $\left[\pm\mp+\pm\mp 45\right]_T$

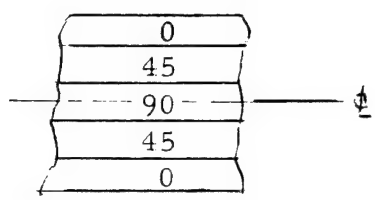
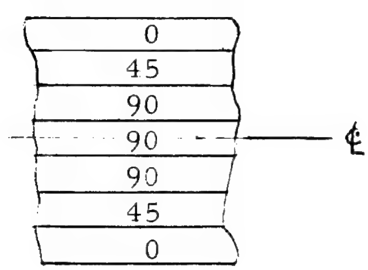
Note that, in condensing signs, the sign of the center lamina of an odd number is left uncombined.

4.3 Symmetric Laminates

Symmetric laminates with an even number of laminae still list the laminae in sequence, starting at one face, but stopping at the plane of symmetry instead of continuing to the other face. A bracket subscript S indicates only one-half of the laminate is shown:

Laminate	Code
	$\left[90/0_2/45\right]_S$

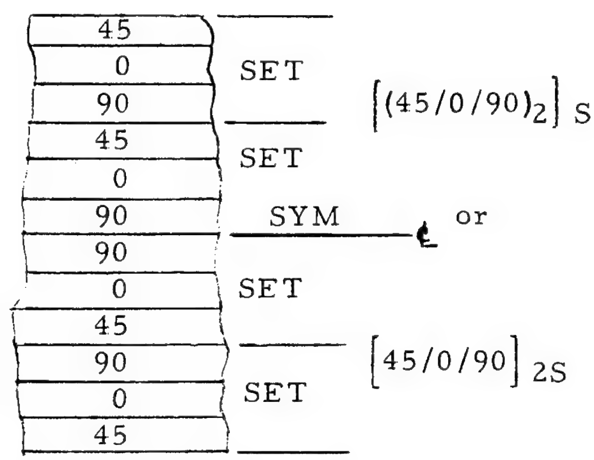
Symmetric laminates with an odd number of laminae are coded the same as even symmetric laminates, except that the center lamina, listed last, is overlined to indicate that half of it lies on either side of the plane of symmetry:

Laminate	Code
	$\left[0/45/\overline{90}\right]_S$
	$\left[0/45/90/\overline{90}\right]_S$

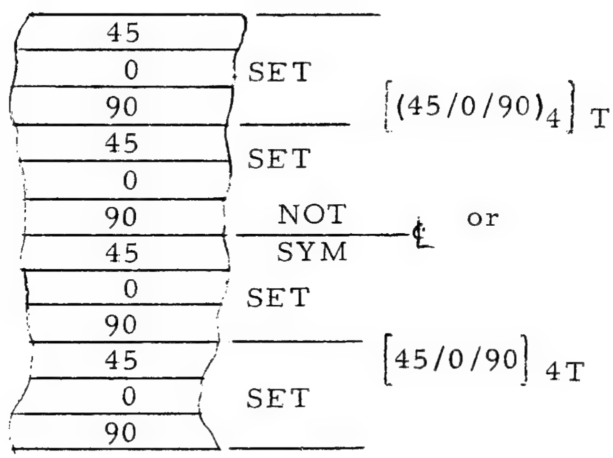
4.4 Sets

Repeating sequences of laminae are called sets and are enclosed in parentheses. A set is coded in accordance with the same rules which apply to a single lamina:

Laminate Code



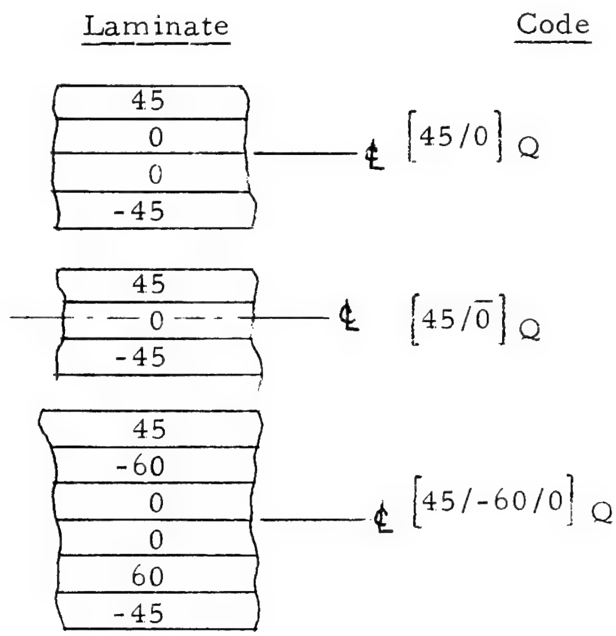
on the other hand:



Laminates are often composed of a single repeated set. When it is desired to refer to the laminate in a generic sense, or when the number of sets has yet to be determined, as in the sizing stages of design, the coefficient n will be used with the bracket subscripts T and S instead of a numerical coefficient.

4.5 Quasi-Symmetric Laminates

Laminates which would be symmetrical about the center plane, except that the halves of corresponding pairs of laminae are of different sign, are said to exhibit quasi-symmetry. These are coded in the same manner as symmetrical laminates except for the introduction of the bracket subscript Q in place of the subscript S. The direction of the positive angle is assumed clockwise:



SwRI-S3-102

GENERAL SPECIFICATION

COMPOSITE TUBE FABRICATION

Date: 3-27-70
Prepared by: G. Commerford
Approved by: G. Grimes

SwRI-S3-102

GENERAL SPECIFICATION
COMPOSITE TUBE FABRICATION

(Glass, Graphite, or Boron/Plastic Composite Material)
Cured Tube Fiber Volume: Boron/Epoxy-50%
Graphite/Epoxy-60%
Glass/Epoxy-60%

Purpose: The tube fabrication unit shall be used in the preparation of advanced fiber reinforced plastic composite tubes for uniaxial and biaxial testing programs. These must be high quality specimens which will be produced in small lots.

Capability: Tube size range is anticipated to be from 3/4 inch to 4 inches I. D. by 20 inches long. Thickness of tube wall will be a minimum of 0.021 inch to a maximum of 0.125 inch for the 3/4 inch I. D. and a maximum of 0.250 inch for the 4 inch I. D. Layup should be accurate, with each layer in intimate contact with the next one starting with the first layer in intimate contact with the tool. Details of processing to be in accordance with prepreg manufacturers instructions or the results of processing studies.

Fiber Orientation: The tube layup may consist of unidirection fibers at 0° or 90° to the tube axis, bidirectional $0^{\circ}/90^{\circ}$ or $\pm 45^{\circ}$, or a multidirectional angleply of balanced construction.

Cure Process: The tubes are to be cured, 1) in a three-piece female mold with internal pressure where the O. D. is the critical dimension, or 2) on a male mold with a vacuum bag or autoclave for pressure when the I. D. is to be controlled. The cure would be accomplished in a controlled-temperature oven or in an autoclave if the male mold-vacuum bag system requires greater pressure.

SwRI-S3-302

PROCESS STANDARD FOR GRAPHITE/EPOXY COMPOSITE LAMINATE FABRICATION

Date: 8/14/70
Prepared by: G. Commerford
Approved by: Glenn C. Grimes

SwRI-S3-302

PROCESS STANDARD FOR GRAPHITE/EPOXY COMPOSITE LAMINATE FABRICATION

1.0 SCOPE

This process standard establishes the procedures for the fabrication and quality control of graphite fiber/epoxy resin laminated panels and tubes to be used in evaluations of various physical properties.

2.0 REQUIREMENTS

2.1 Materials

2.1.1 The resin impregnated graphite fibers shall satisfy the requirements of Specification SwRI-S3-202 as specified by the applicable purchase order. Resin system and type of graphite fiber and form of prepreg material shall be specified in the applicable purchase order.

2.1.2 Secondary materials to be used in the fabrication of graphite/epoxy laminates shall be as listed below or equivalent materials:

Bleeder and vent plies; 120 and 181 dry glass fabric - J.P. Stevens Co.
Separator cloth; TX-1040 glass fabric - Pallflex Corp.
Boundary support; 0.125-in. thick Coroprene - Armstrong Cork Co.
Seal ply; 0.001-in. Mylar film - E.I. duPont de Nemours Co.
Release agent; Ram-Part 87-X76 - Ram Chemicals Co.
Pressure bag for tube fabrication; Silicone rubber tubing -
Rubber Craft of California

2.2 Storage of Materials

2.2.1 Store fresh prepreg material in a sealed plastic bag at $0^{o}F$ or as recommended by the manufacturer.

2.2.2 When material is to be used, it shall be removed from the $0^{o}F$ storage and brought to room temperature before plastic bag is unsealed. Condensed moisture should be wiped from the bag before unsealing. A record of time out of storage shall be maintained and material must be resubmitted for acceptance testing if accumulated time at room temperature exceeds 15 days.

2.2.3 If a partially or completely laid-up laminate is to be placed in storage at $0^{o}F$, it shall be sealed in a plastic bag. When removed from storage it shall be allowed to warm to room temperature before the plastic bag is unsealed.

2.3 Tooling

2.3.1 Lay-up plates for flat panels of uniform thickness may be steel or aluminum. One surface shall have an acceptable smoothness for lay-up. A caul plate of the same material and surface smoothness as the lay-up plate shall be used to apply pressure to the top of the lay-up in the heated-platen press cure of flat panels.

2.3.2 The tooling for tubes shall be steel with chromium plating on the internal surface of the outer sleeve of the tool. The inner sleeve of the tool shall be covered with silicone rubber tubing to form an expandable inside mandrel for the tube.

2.4 Fabrication

2.4.1 Preparation for fabrication shall include an overall test plan which describes the number and type of test specimens required and the laminated panels and tubes required. Engineering drawings shall be prepared if necessary. A process instruction sheet shall be completed listing the part number, material batch number, ply thickness and orientation, lay-up instructions and cure cycle.

2.4.2 Lay-up of the graphite/epoxy laminates shall be performed in a clean laboratory where temperature and relative humidity are maintained at $65^{\circ}F$ to $75^{\circ}F$ and 40% to 65%, respectively. A lab coat of nylon or equivalent tight-weave, smooth surface fabric or a non-linting disposable fabric is to be worn when laying-up laminates or preparing materials for adhesive bonding. Safety glasses or face shield shall be worn when cutting prepreg or when handling cleaning materials.

2.4.3 Lay-up tool shall be cleaned to remove all foreign material. If required the surface shall be polished to provide the required smoothness. Wipe with solvent (MEK) and air dry. Apply release agent in accordance with manufacturer's instructions or dry for 15 minutes, buff and repeat with a second coat.

2.4.4 Remove prepreg from $0^{\circ}F$ storage and warm to room temperature before removing from the sealed plastic bag. Cut prepreg to size for each ply as indicated on the process instruction sheet. This may be done with a sharp knife and metal straight-edge or with a large

paper shear. Prepreg which is not to be used immediately shall be resealed in a plastic bag and returned to $0^{o}F$ storage as soon as possible making note of time out of storage on the material storage log sheet.

2.4.5 For small flat panels a 2-in. wide boundary support may be cut from a single piece of Coroprene so that there are no joints at the corners. For larger panels the boundary support may be made up of 2-in. wide strips of Coroprene. The corner joints may be filled to prevent leakage of resin. The boundary support shall be applied to the tool plate and used as the lay-up pattern for simple rectangular panels.

2.4.6 Lay-up prepreg, separator and bleeder plies in sequence indicated on process instruction sheet for flat panels (see Fig. A.1). Use roller to compact each ply of prepreg. Inspect each prepreg ply prior to use and repair any gaps or defects. Discard any material which contains flaws which cannot be repaired. Ply orientation shall be accurate to $\pm 0.50^{o}$. Gaps within prepreg or between adjacent strips shall not exceed 0.030 inch. Tube lay-ups shall be stacked as indicated on the process instruction sheet and then rolled onto the expandable mandrel.

2.4.7 Cover flat panel lay-up with Mylar film which extends to outer edge of boundary support. Perforate film on 2-in. centers starting one inch or less from each edge of lay-up. Place vent ply of 181 glass fabric extending to outer edge of boundary support over Mylar film and cover with caul plate. If the panel is to be left overnight or longer before cure, it should be sealed in a plastic bag and placed in $0^{o}F$ storage. On removal

1. Separator Cloth (TX 1040) or Peel Ply
2. Boron or Glass Fabric Laminate
3. Separator Cloth (TX 1040)
4. Bleeder Plies (120 Glass Fabric--1 ply per 4 plies Boron or 2 plies Glass Fabric)
5. Mylar Film (Overlaps Boundary Support)
6. 181 Vent Ply (Overlaps Tool)
7. Boundary Support

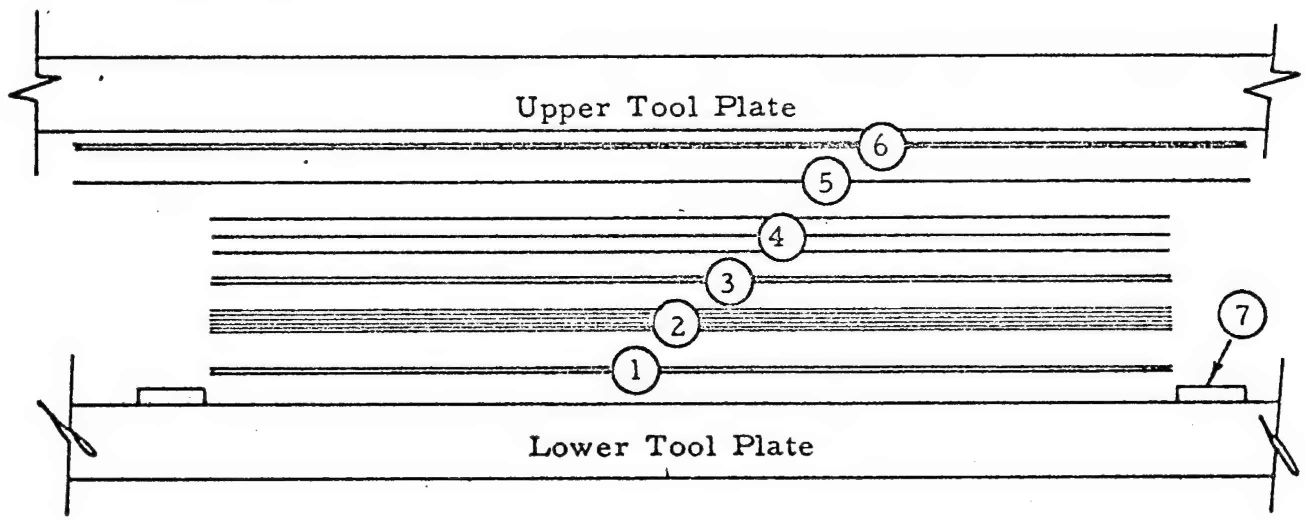


FIGURE A.1 TYPICAL PANEL LAY-UP

from $0^{\circ}F$ storage, the lay-up must be allowed to warm to room temperature before opening the plastic bag. A tube lay-up rolled onto the expandable mandrel and placed inside the tube mold may be stored at $0^{\circ}F$ until ready for cure if the vacuum connection of the mold is closed or covered. The mold may be placed in the curing oven directly from $0^{\circ}F$ storage without waiting for it to warm to room temperature.

2.4.8 Cure time, temperature and pressure are dependent on the type of resin and shall be specified on the process instruction sheet.

3.0 INSPECTION OF CURED LAMINATES

3.1 Dimensions

Thickness of flat panels shall be measured at a number of points around the periphery and at least 1/2 in. from the edge. The average of these measurements will be recorded as the nominal panel thickness. Tubes will be measured for outside diameter near each end and the center on two diameters 90° apart. These values shall be averaged for the nominal tube outside diameter. Tube wall thickness shall be measured at four points at each end of the tube after trimming the tube ends and cutting off quality control samples. The average of these measurements shall be recorded as nominal tube wall thickness.

3.2 Ultrasonic Test

A through-transmission ultrasonic inspection of all laminates shall be performed to detect areas of unbond, foreign matter inclusions, or other defects.

3.3 Physical-Mechanical Properties

Flat panels shall be cut to provide quality control samples in addition to the required test specimens. QC samples shall be submitted for longitudinal and transverse flexure, short beam horizontal shear, specific gravity, and fiber content determinations. QC samples cut from tube shall be submitted for specific gravity and fiber content determinations.

SwRI-S3-400

ANALYTICAL METHODS FOR SPECIFIC GRAVITY AND GRAPHITE CONTENT OF GRAPHITE/EPOXY LAMINATE SPECIMENS

Date: 9/15/70
Prepared by: W. McMahon
Approved by: Glenn C. Grimes

SwRI-S3-400

ANALYTICAL METHODS FOR SPECIFIC GRAVITY AND GRAPHITE CONTENT OF GRAPHITE/EPOXY LAMINATE SPECIMENS

I. Specific Gravity

Determined according to ASTM D792-66.

II. Graphite Content

1. Weigh the specimen to nearest 0.0001 gram on an analytical balance. The specimen should be selected so that it weighs 0.5 to 1.5 grams.

2. Place specimen in a 100 ml beaker, add 50 ml concentrated nitric acid, cover with watch glass and heat on a hot plate 2 hours at 160 to 180°F (acid temperature).

3. Separate the acid from the fibers by decanting into a 250 ml beaker, add 50 ml concentrate nitric acid to the fibers and heat on a hot plate (as in step 2) for 1-1/2 to 2 hours. Retain the nitric acid extract contained in the 250 ml beaker.

4. Separate the second acid extract of the fibers by decanting into the 250 ml beaker. The combined nitric acid washes (100 ml) are retained for step 6.

5. Add 80 to 90 ml of distilled water to the graphite fibers, stir and allow to soak while performing step 6 below.

6. Filter the combined nitric acid extracts (from step 4) through a clean 50 ml sintered glass filter crucible rigged for vacuum filtration, which has been dried for 1 hour at 150°C and weighed

to the nearest 0.0001 gram. Rinse the beaker (wash down sides) with 10-15 ml of concentrated nitric acid, two 50 ml water rinses, and 25 ml of acetone, filtering each rinse through the filter crucible. Rinse down the sides of the filter crucible with acetone to dissolve the precipitated resin.

7. Decant the water wash (step 5) from the fibers by pouring through the filter crucible.

8. Add 80-90 ml of distilled water, stir and repeat step 7.

9. Wash the fibers twice with 80-90 ml of acetone, decanting the wash into the filter crucible. Carefully transfer the fibers to the filter crucible with the second acetone wash. Using a wash bottle, containing acetone, carefully rinse all the fibers from the beaker into the filter crucible.

10. Wash the fibers again with acetone and water by first filling the crucible twice with acetone, followed by filling the crucible twice with distilled water, using vacuum to remove the wash fluids.

11. Dry the crucible 1 hour in a 150°C drying oven, cool in a desiccator for at least 1-1/2 hours or overnight, and reweigh.

12. Calculation:

$$\% \text{ by weight of graphite} = \frac{\text{wt. fibers}}{\text{Wt. sample}} \times 100$$

SwRI-S3-401

TEST STANDARD FOR FIBROUS COMPOSITE TENSILE SPECIMENS

Date: 9/30/70
Prepared by: G. Wolfe
Approved by: Glenn C. Grimes

SwRI-S3-401

TEST STANDARD FOR FIBROUS COMPOSITE TENSILE SPECIMENS

1.0 PURPOSE

It is the purpose of this standard to provide a standardized technique for measuring the static tensile properties of boron/epoxy and graphite/epoxy composites subjected to a monotonically increasing load to failure.

2.0 APPLICABLE DOCUMENTS

"Structural Design Guide for Advanced Composite Applications, 2nd Edition, Sections 7.3.1 and 7.3.2.

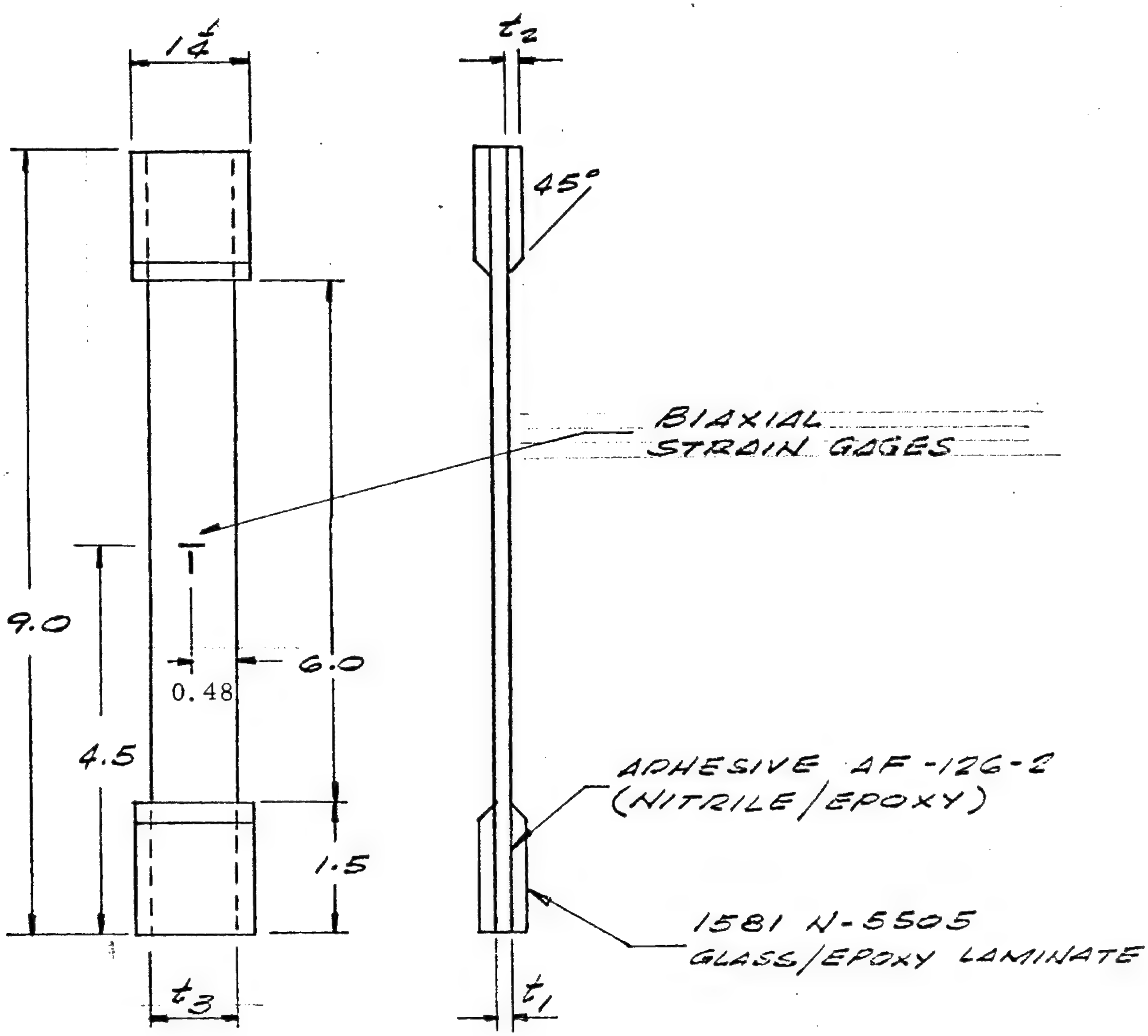
3.0 SCOPE

This standard covers both boron/epoxy and graphite/epoxy materials up to 18 plies thick. Measurements shall include load/biaxial strain data to obtain biaxial stress-strain curves to failure under constant strain rate conditions.

4.0 SPECIMEN PREPARATION AND INSTRUMENTATION

Specimens are to be laid out and cut from a suitable size panel to the dimensions shown on the drawing below. Subsequent to cutting out the specimens, tabs are bonded onto the specimens in groups of three or more (see drawing below). Strain gages are to be as described on the drawing.

SwRI Standard Tensile Specimen for Composites



Notes:

1. t_1 - boron/epoxy or graphite/epoxy specimen $\leq$ 18 plies thick unidirectional or angleply
2. t_2 - fiberglass/epoxy tabs 0.100 $\pm$ 0.01 in. thick (approximately 12 plys 1581)
3. Strain gages - Micro-Measurements 06-250BF-350
4. Tolerances: X $\pm$ 0.1; XX $\pm$ 0.04; Fractions $\pm$ 1/16 } unless noted otherwise
5. t_3 - boron/epoxy 0.96 in. wide; - graphite/epoxy 0.75 in. wide } sides to be smooth, splinter free and flat and parallel within 0.015
6. Diamond cutoff wheel to be used in sizing specimens from panel
7. Tabs are bonded on in groups of three specimens or more at time with strip tabs leaving 3/8 in. spacing between specimens. Individual specimens are then sliced off by cutting through tab material.
8. Use stand Instron wedge grips with fine serrations.
9. Tab bonding: cure adhesive 1 hr at 275°F at 50 psi in heated platen press.

5.0 TESTING

In addition to the strain gages, a clamp on extensometer with a 2-in. gage length will be used on each specimen in order to control the strain rate during test and to provide back-up load-deflection curves should they be needed. Loading should be on a monotonically increasing basis at a constant strain rate of 0.00125 in./min over a 2-in. gage length. Load and strain shall be recorded automatically, either continuously or at known automatically spaced time intervals.

6.0 FAILURE ANALYSIS

All specimens shall be categorized as to failure type, such as (1) net section tension, (2) delamination, (3) diagonal shear, (4) brooming net section tension delamination, or (5) any combination thereof. Location of the failure shall be measured and recorded.* Any type failure between tabs is acceptable. Any type failure under the tabs is unacceptable. Complete failure description, type and location shall be recorded.

7.0 DATA REDUCTION

Raw data shall be appropriately processed to yield stress-strain data from which biaxial stress-strain curves may be plotted. Proportional limits, knees, moduli, Poisson's ratio, and ultimate strengths shall be located, calculated, and tabulated along with related strains. Complete computerized data reduction, plotting, and the tabulation of data is acceptable.

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*Photographs of typical failures shall be made for record.

Date: 8/1/70
Prepared by: G. Commerford
Approved by: Glenn C Grimes

SPECIFICATION SwRI-S3-202

MATERIAL PROCUREMENT SPECIFICATION FOR RESIN IMPREGNATED GRAPHITE FIBER TAPE AND BROAD GOODS

1.0 INTRODUCTION

1.1 Scope

This specification establishes the minimum physical and mechanical requirements for resin impregnated multifilament graphite yarn and fiber collimated tape and broad goods. The impregnated tape and broad goods covered by this specification are to be used in fabricating composite panels, tubes or structural components for use in various research and development test programs.

1.2 Classification

The graphite composite material systems specified herein shall be classified according to useful temperature range, type of fiber, fiber cleaning and fiber form as described below.

1.2.1 Resin

The resin used in the manufacture of material to this specification shall be of high quality, entirely suitable for the purpose intended and as specified herein or in the applicable purchase order. The resin shall be a low pressure type. The cured resin shall not be corrosive to metals. The resin shall be suitable for the impregnation of graphite yarns, fibers and broadgoods and shall be free of foreign matter. The resin shall

be further classified according to its maximum service temperature as follows:

Type I - General Purpose (200°F)

Type II - Moderate Heat Resistant (300°F)

Type III - General High Heat Resistant (400°F)

1.2.2 <u>Graphite Fibers</u>

Classification of the graphite reinforcement specified herein shall be according to the fiber type, surface cleaning or treatment and manufacturing process as follows:

Fiber Classification A - Rayon Precursor
B - Polyacrylonitrile (PAN) Precursor

Surface Type 1 - untreated
2 - surface treated

Process and Form a - Batch, length less than 6 feet
b - Batch, longer than one meter, less than 1000 inches
c - Continuous process, continuous length of 1000 inches or more

2.0 REQUIREMENTS FOR PREIMPREGNATED GOODS

2.1 <u>General</u>

Preimpregnated material conforming to this specification shall consist of parallel, in-plane bundles of graphite filaments impregnated with a specified resin system. The preimpregnated materials are classified according to the form in which the graphite filament bundles are used as follows:

Class I - filaments spun into yarn with 60-70 yarn ends per inch of prepreg width (turns per inch of yarn length to be specified)

Class II - filaments are tow with 4-30 tow ends per inch of prepreg width

2.1.1 Material Form

The material to be supplied under this specification shall be in accordance with the applicable purchase order. Material in the form of unidirectional 3-inch wide tape or wide goods of specified width and length, or woven fabric of specified weave and fiber count shall be indicated in the purchase order to conform with the intended use of the material.

2.1.2 Splices

Splices of ends of tows or yarns shall not be made at less than 2-foot intervals or directly across the tape or sheet.

2.1.3 Alignment

The preimpregnated tows or yarns shall be well aligned. Imperfections in filament alignment within the yarn resulting in a deviation of over 20° from the two or yarn axis over a length of 1/2 inch will be considered a fiber defect. Occurrence of such defects in over 10% of the tows or yarns in a 2-foot long section of 3-inch wide tape or sheet stock shall be cause for rejection. Defects may be removed during impregnation if splices do not exceed the requirements of 2.1.2.

2.1.4 Workmanship

Preimpregnated fibers submitted for qualification or acceptance under this specification shall be of high quality workmanship and shall be free of major defects and contaminants detrimental to fabrication or performance of finished parts.

2.1.5 Shelf Life, Work Life and Storage

The shelf life of the preimpregnated materials shall be such that they meet the requirements of this specification as follows:

Material	Shelf Life	
	75^{o}	$0^{o}F$ or below
All Classes	10 days*	3 months

*From date of shipment from vendor

The material shall possess sufficient room temperature working life that the requirements of paragraphs 2.1.6 are met after exposure to a room temperature environment (humidity not to exceed 50%) for a continuous period of 12 days. Material shall be stored at $0^{o}F$ or below. A record shall be maintained of the periods of time any roll has been out of refrigeration.

2.1.6 Properties

The materials submitted to this specification shall meet the mechanical and physical properties given below:

Physical Properties of Uncured Materials

Property	Requirements
Tack	Adhere to a vertical surface
Resin Content (% by weight)	40 $\pm$4%
Volatiles (% by weight)	3% (max)
Alignment	See paragraph 2.1.3.

Mechanical Property Requirements for Cured Laminates

Type of Test	Temp. ^oF	Minimum Ultimate Average Values (ksi)		
		Type I	Type II	Type III
0^o Flexure	R.T.	220	200	190
	200	180	-	-
	300	-	110	-
	400	-	-	100
90^o Flexure	R.T.	10	8	8
	200	8	-	-
	300	-	4	-
	400	-	-	4
Horizontal Shear	R.T.	15	14	13
	200	8	-	-
	300	-	5	-
	400	-	-	5

3.0 QUALITY ASSURANCE

3.1 Inspection

The supplier shall be responsible for the performance of all material certified to this specification and processed according to his instructions and those delineated in SwRI-S3-302.

3.2 Classification of Tests

Testing of material procured to this specification shall be classified as follows:

3.2.1 Qualification Tests

Qualification tests are those tests accomplished on those materials submitted for approval as a suitable product. Qualification consists of tests for all the requirements of this specification. Failure of the material to meet any of the test requirements shall be cause for rejection. Upon successful completion of tests, the material will be qualified. Material which has been previously qualified to another specification whose requirements equal or exceed those specified herein may be qualified at the discretion of the R&D Program Project Leader.

3.2.2 Acceptance Tests

Acceptance tests are those tests performed on previously qualified materials manufactured and submitted for acceptance under contract or order to the requirements of this specification.

SwRI reserves the right to verify all acceptance testing and the failure of any test requirement shall be cause for rejection.

3.3 Production Lot

A production lot of impregnated graphite fiber materials shall consist of all rolls of fiber impregnated in a single manufacturing operation with a single batch of resin and offered for acceptance at one time.

3.4 Certification

Each production lot of impregnated graphite fiber material offered for inspection shall be certified by the supplier that the raw materials (graphite fibers and resin) and processing used in the manufacture of the material being submitted are the same as those in the qualification sample. All material submitted shall conform to the requirements of this specification and shall be accompanied by a certification sheet.

3.5 Defects

Any defects which were not detected during lot acceptance testing and which become apparent during the subsequent use of the material shall be cause for rejection of the unused portion of the roll provided such defects are cause for rejection under the requirements of this specification and are not a result of mishandling, improper storage, or expiration of shelf life.

3.6 Rejection and Retest

In case of failure of the sample to meet specified requirements an additional sample of the same production lot may be tested. If this sample fails the specified test the material it represents shall be rejected.

3.7 Testing

3.7.1 Sampling

A random sample from each production lot shall be selected as follows: After allowing the package to come to room temperature,

open the package, discard the outer layer of material and remove sufficient material to perform the required tests. The roll of material shall be repackaged and returned to refrigerated storage. The sample shall be properly identified and if not to be used immediately, wrapped in a moisture proof bag and refrigerated until used.

3.7.2 Conditions of the Test

For purposes of this specification "room temperature" or "R.T." is defined to be $65^{o}F$ to $80^{o}F$ and 50% $\pm$ 10 relative humidity. Elevated temperature tests are to be performed on specimens after 30 minute exposure to the test temperature.

3.7.3 Physical Tests

3.7.3.1 All physical testing required shall be performed in accordance with the requirements of this specification and SwRI-S3-302.

3.7.4 Mechanical Tests

All mechanical testing shall be performed in accordance with the requirements of this specification. Fabrication processes shall be as specified in SwRI-S3-302.

4.0 PACKING AND SHIPPING

4.1 Packaging of Individual Tape Rolls or Sheets

4.1.1 Continuous Tape

Continuous tapes shall be packaged under tension as rolls on 8" inside diameter tubes. The width of the tube shall be at least one

inch more than the width of the goods packaged thereon. A nonadherent paper or plastic separator sheet of a contrasting color shall be used on one side of each layer.

Note: Tensioning of the wide tape shall be controlled to prevent wrinkling or buckling of the inner layers. Packaged goods shall be sealed individually within a moisture proof plastic bag. An identification tag as per Section 4.4 shall be placed within each bag prior to sealing.

4.1.2 Sheet Stock

Sheet stock size shall be as specified in the purchase order. It shall be supplied with a separator sheet on each side. The separator sheet shall be a nonadherent paper or plastic sheet of a contrasting color.

4.2 Packing

Packaged materials shall be packed in clean dry containers so constructed as to insure acceptance by common or other carrier for safe transportation at the lowest rate to the place of delivery specified by purchase or contract. Cartons shall be so constructed and insulated that solid carbon dioxide may be added to insure that temperature of material will be at $0^{\circ}F$ or lower upon receipt.

4.3 Shipping and Receiving

Cartons containing preimpregnated goods shall be shipped by air. Cartons shall be delivered from the terminus of the common carrier to

the delivery site specified on the purchase order or contract with minimum stopover and delay. Upon delivery, shipping cartons shall be opened to ascertain that solid carbon dioxide remains in cartons. Material shall immediately be unpacked and placed in $0^{\circ}F$ or lower storage.

4.4 Marking

4.4.1 Packages

Each package shall be legibly and durably marked by means of a securely attached tag in such a manner and location that it remains in place until all the representative material is used. Marking shall include, but not be limited to, the following information:

Nomenclature
This specification number, type and class
Date of impregnation
Width of material
Linear feet
Manufacturer's batch no.
Manufacturer's designation

In addition, the following prominent precautionary marking shall be included: "Ship and Store at $0^{\circ}F$."

4.4.2 Containers

Packing containers shall be marked with the following information:

a. Number and revision letter of this specification
b. Type and class of material for this specification
c. Manufacturer's and supplier's name(s)
d. Material trade name
e. Supplier's lot number(s)
f. Fragile
g. Nominal width and length per roll
h. Number of rolls in packaging container
i. Shipping and storage requirements

j. Shipping date
k. Temperature history label

5.0 APPLICABLE SPECIFICATIONS

The following publications shall be applicable to the extent specified herein, or as defined on the contract or purchase order. These publications shall be in effect as of the issues listed, except the SwRI specifications shall be the latest issue published. Compliance with any other issues of these publications requires prior written approval. Insofar as any of the publications referred to herein conflict with the requirements of this specification, this specification shall govern.

5.1 SwRI Specifications

SwRI-S3-101	General Specification, Lamination Orientation Code
SwRI-S3-102	General Specification, Composite Tube Fabrication
SwRI-S3-302	Process Standard for Graphite/Epoxy Composite Laminate Fabrication
SwRI-S3-400	Analytical Methods for Specific Gravity and Graphite Content of Graphite/Epoxy Laminate Specimens

APPENDIX II

SELECTED, TYPICAL EXPERIMENTAL DATA ON FLAT PANELS

APPENDIX II. 1

STATIC TENSION

TABLE II.1

STATIC TENSION, C-47

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS - Treated   Lam. Orient. $[0]_{3T}$

Matrix - ERL 2256   No. of Plies 3

Load Orient. 0^{o}

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☒, Comp ☐, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: Straight Sided, SwRI 03-401

Soak at Temp: - °F for - hr   Test Temp. RT °F

Property		Panel No.	C-47							Ave	S.D.
		Spec. Ident.	5-3A	5-3B	5-3C						
Stress (ksi)	F_{pl}										
	F__										
	F__										
	F__										
	F_{ult}		206.8	191.8	135.0					177.9	37.9
Modulus $E, Gx10^{-6}$	E or G (Primary)		24.03	24.05	21.93					23.34	1.22
	E' or G' (Secondary)										
Strain in./in.	Proportional Limit	ϵ_1									
		ϵ_2									
		ϵ_{45}									
	Ultimate	ϵ_1	0.00760	0.00720	0.00510						
		ϵ_2									
		ϵ_{45}									
Specimen Width (in.)			0.499	0.500	0.500						
Specimen Thick. (in.)			0.025	0.027	0.024						

Strain Gage No. EA 03-250 BF-350   Properties Based on

Extensometer   Nominal ☐; Actual ☒

Filament Count -- /in.   Void Content 2.88 %   Ply Thick. .00844 in.

Fil. Vol. Fract. 0.648   Resin Wt. Fract. 0.____   Lam. Density .0573 $lb/in.^3$

Laminate: Tape or Matrix Design broadgoods-M.L.   Manuf. Fiberite

Balance Ply N/A   Cure Spec SwRI S3-303

Organization: SwRI

Comments:

*Indicates Strain Measurement by Resistance Strain Gages.

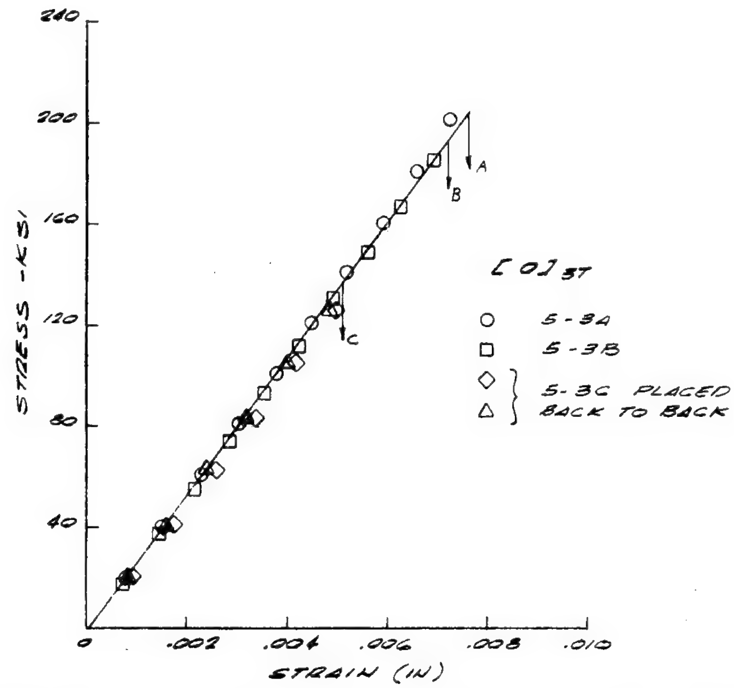


FIGURE II.1. STRESS VS LONGITUDINAL STRAIN, 5-3A, 5-3B AND 5-3C (STRAIN GAGE DATA)

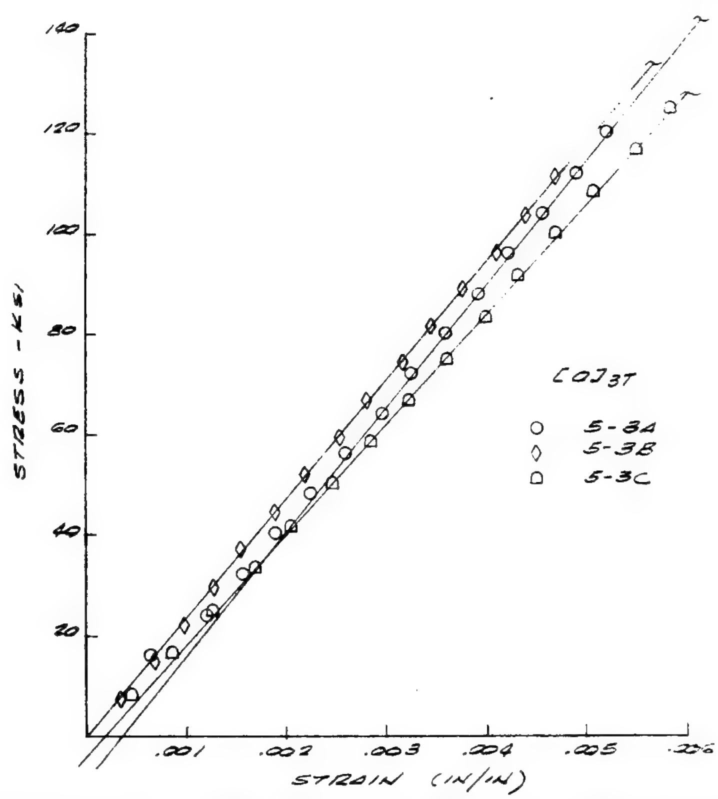


FIGURE II.2. STRESS VS LONGITUDINAL STRAIN, 5-3A, 5-3B AND 5-3C (EXTENSOMETER)

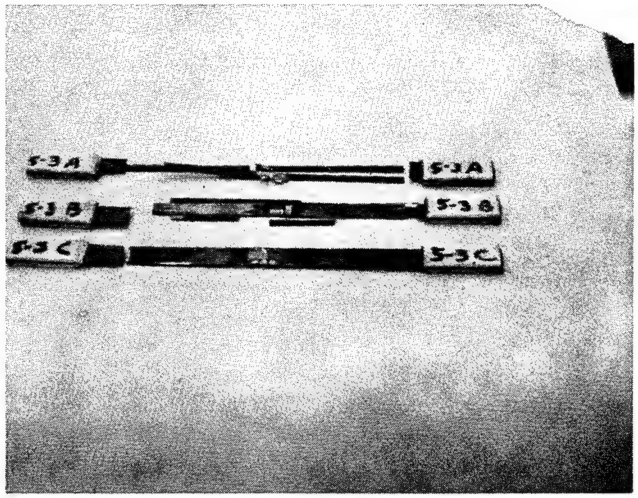


FIGURE II.3. UNIAXIAL TENSILE SPECIMENS 5-3A, B, C AFTER FAILURE, $[0]_{3T}$

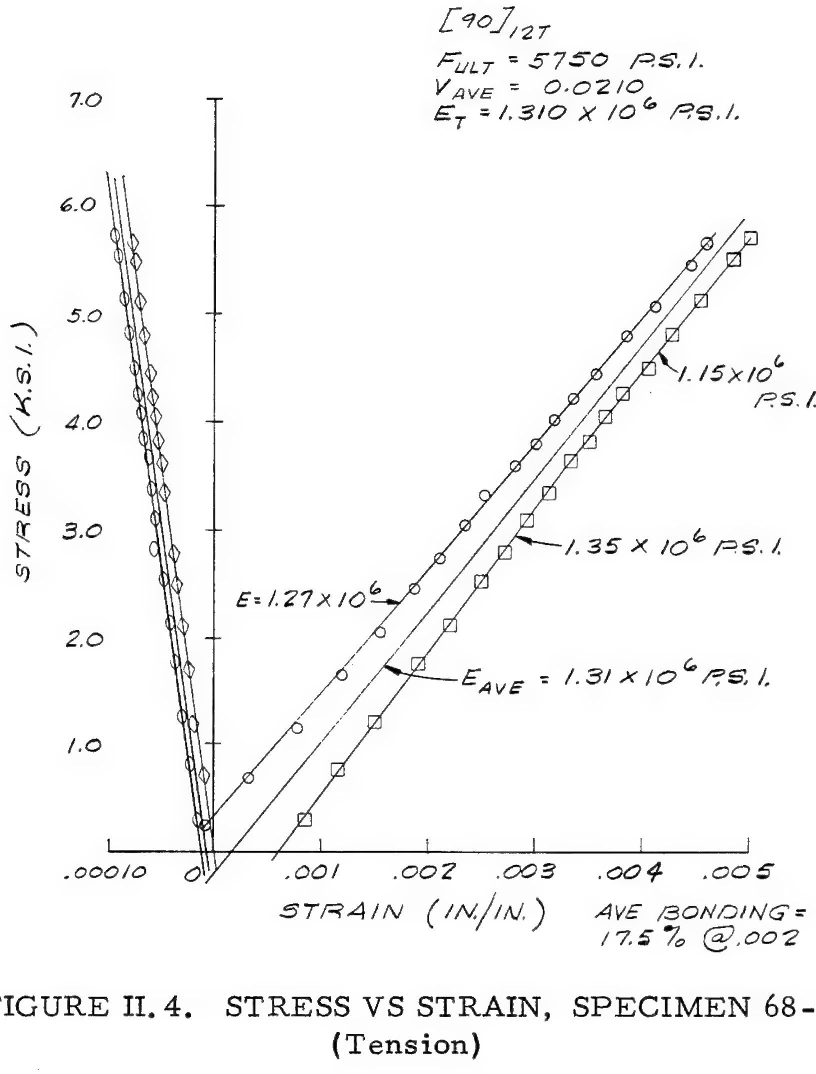


FIGURE II.4. STRESS VS STRAIN, SPECIMEN 68-A (Tension)

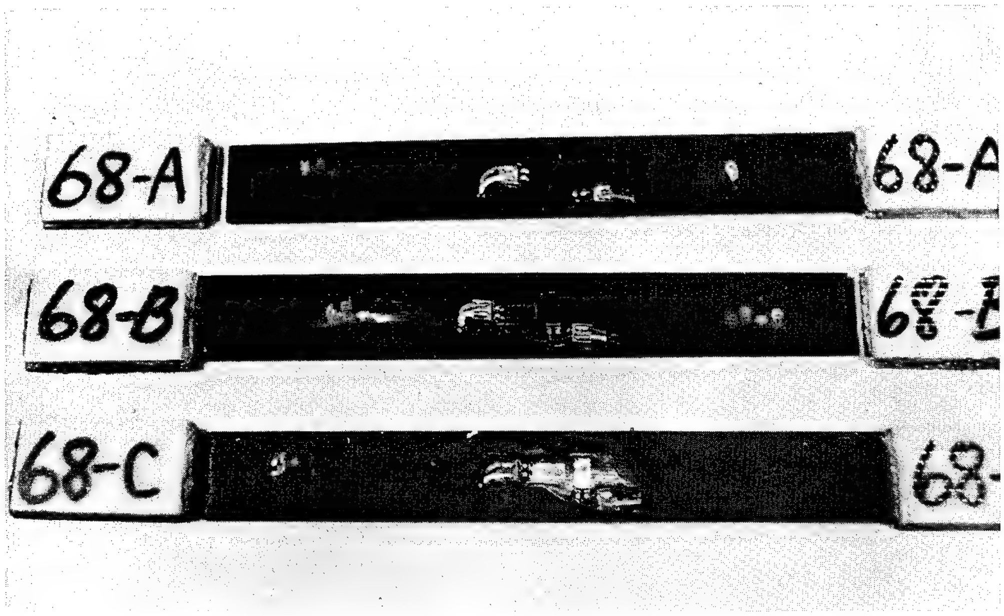


FIGURE II. 5. UNIAXIAL TENSILE SPECIMENS 68-A, B, C AFTER FAILURE, $[90]_{12T}$

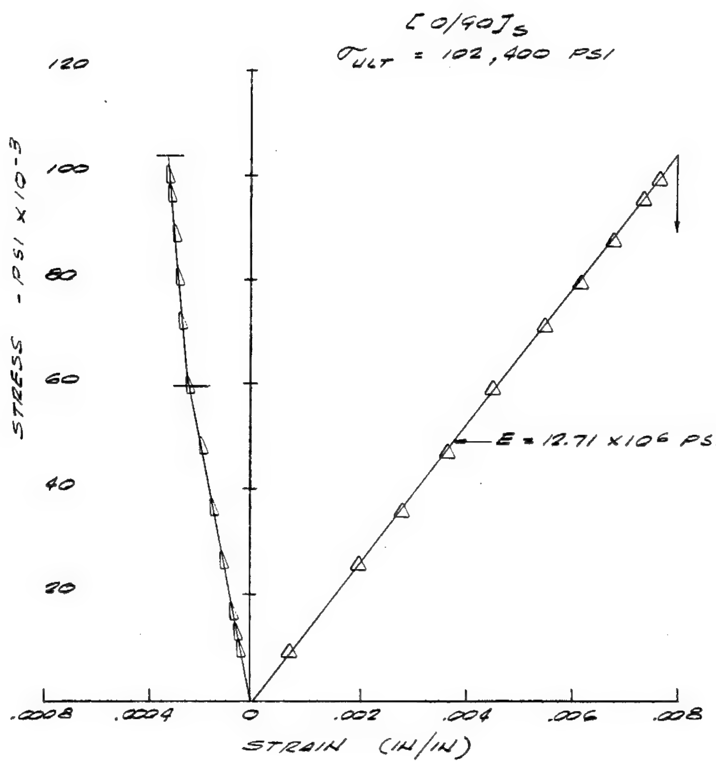


FIGURE II. 6. STRESS VS STRAIN, 63-N

TABLE II.2

STATIC TENSION, C-68

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS   Lam. Orient. $[90]_{12T}$

Matrix - ERL-2256   No. of Plies 12

Load Orient. 0^{o}

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☒, Comp ☐, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: SwRI 03-401

Soak at Temp: -- °F for -- hr   Test Temp. RT °F

Property		Panel No.	C-68								
		Spec. Ident.	68-A	68-B	68-C					Ave	S.D.
Stress (ksi)	F_{pl}			2.85							
	F__										
	F__										
	ν		0.0210	0.0200	0.0190					0.020	
	F_{ult}		5.75	5.08	6.02					5.62	
Modulus $E, G \times 10^{-6}$	E or G (Primary)		1.31	1.34	1.22					1.29	
	E' or G' (Secondary)			1.16							
*Strain in./in.	Proportional Limit	ϵ_1		0.0022							
		ϵ_2									
		ϵ_{45}									
	Ultimate Ave.	ϵ_1		.00410	.00487					0.00448	
		ϵ_2		-.000078	-.00009					-0.000084	
		ϵ_{45}									
Specimen Width (in.)			0.749	0.750	0.748					0.749	
Specimen Thick. (in.)			0.113	0.114	0.115					0.114	

Strain Gage No. MM EA 03-250BF-350

Extensometer B. Dualrange TSM-D-1047

Properties Based on Nominal ☐; Actual ☒

Filament Count -- /in. Void Content 0.82 % Ply Thick. 0.00946 in.

Fil. Vol. Fract. 0.5639 Resin Wt. Fract. 0. -- Lam. Density 0.0551 lb/in.^{3}

Laminate: Tape or Matrix Design Broadgoods-M. L. Tow Manuf. Fiberite

Balance Ply N/A Cure Spec SwRI S3-303

Organization: SwRI

Comments: Average bending: 68A = 17.5%, 68B - 10%, 68C = 12-1/2%

*Indicates Strain Measurement by Resistance Strain Gages.

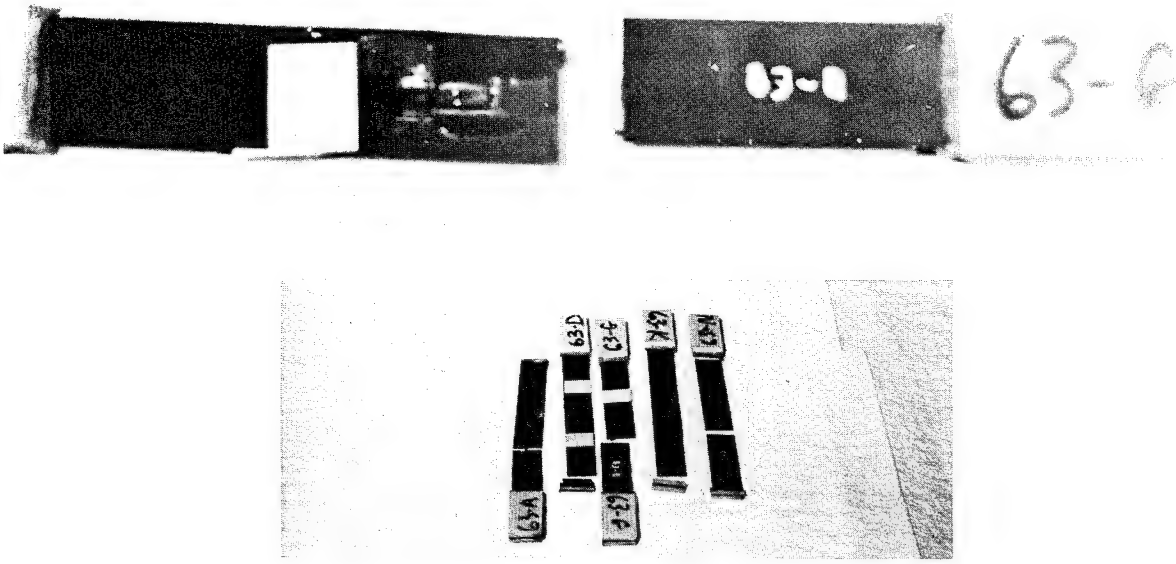


FIGURE II. 7. UNIAXIAL TENSION SPECIMENS 63-A, D, G, K, N AFTER FAILURE, $[0/90]_S$

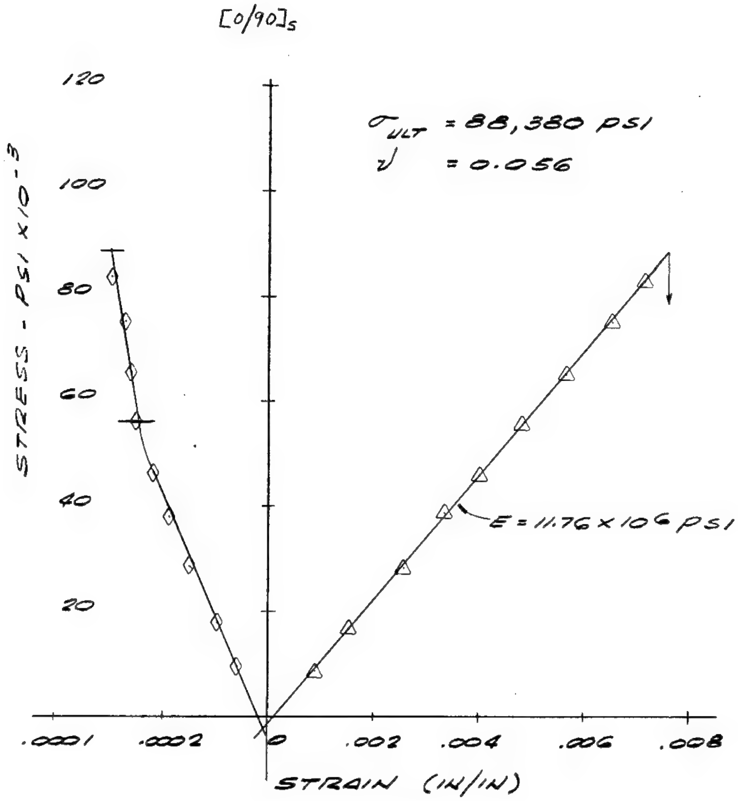


FIGURE II. 8. STRESS VS STRAIN, SPECIMEN 64-L (TENSION)

TABLE II. 3

STATIC STRESS/STRAIN, C-63

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS - Treated   Lam. Orient. $[0/90]_S$

Matrix - ERL 2256   No. of Plies 4

Load Orient. 0^o

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☒, Comp ☐, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: Standard Straight Sided, SwRI 03-401

Soak at Temp: - °F for - hr   Test Temp. RT °F

Property		Panel No.	C-63								
		Spec. Ident.	63A	63D	63G	63K	63N			Ave	S. D.
Stress (ksi)		(1) F_{pl}	54.75	ϕ	51.3	37.5	59.1			48.16	
		F__									
		F__									
		ν	0.0438	ϕ	(3)	0.050	0.050			0.0479	
		F_{ult}	77.98	71.16	79.91	56.84	102.4			77.66	16.53
Modulus E, Gx10^{-6}		E or G (Primary)	8.70(2)	11.52	12.92	12.51	12.71			12.42	
		E' or G' (Secondary)									
*Strain in./in.	Proportional Limit	ϵ_1									
		ϵ_2									
		ϵ_{45}	0.00234								
	Ultimate	ϵ_1	0.00449	0.00021	0.00061	0.00047	0.00077				
		ϵ_2			0.00043	-0.00022	-0.00031				
		ϵ_{45}									
Specimen Width (in.)			0.7502	0.751	0.751	0.750	0.749			0.075	
Specimen Thick. (in.)			0.0359	0.035	0.035	0.035	0.034			0.035	

Strain Gage No. EA-03-250BF-350   Properties Based on

Extensometer   Nominal ☐; Actual ☒

Filament Count -- /in. Void Content .02 % Ply Thick. .00875 in.

Fil. Vol. Fract. 0.5877 Resin Wt. Fract. 0. Lam. Density .0560 lb/in.^{3}

Laminate: Tape or Matrix Design broadgoods-M. L. Manuf. Fiberite

Balance Ply n/a Cure Spec SwRI S3-303

Organization : SwRI

Comments: Strain gages indicate bending in 63-A. Spring loaded grips used on 63A and 63D. 63A strain rate - .03125, others - 0.0125. (1)Longitudinal stress at transverse strain knee; (2)Not used in averages due to excessive bending; (3)Transverse gage questionable.
ϕNo transverse gage.

*Indicates Strain Measurement by Resistance Strain Gages.

FIGURE II. 9. UNIAXIAL TENSION SPECIMENS 64-B, E, H, L, P AFTER FAILURE, $[0/90]_S$

TABLE II.4

STATIC TENSION, C-64

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS - Treated Lam. Orient. $[0/90]_S$

Matrix - ERL 2256 No. of Plies 4

Load Orient. 0^o

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☒, Comp ☐, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: Standard Straight Sided, SwRI 03-401

Soak at Temp: - °F for - hr Test Temp. RT °F

Property		Panel No.	C-64							Ave	S.D.
		Spec. Ident.	64B	64E	64H	64L	64P				
Stress (ksi)	(1) F_{pl}		62.0	65.6	56.8	56.0	53.0			58.68	
	F__										
	F__										
	ν		0.0312	0.0623	0.0237	0.0560	0.0328			0.0412	
	F_{ult}		74.84	96.88	102.1	88.38	74.95			87.43	12.45
Modulus $E, G \times 10^{-6}$	E or G (Primary)		11.87	11.86	12.98	11.76	12.02			12.10	0.50
	E' or G' (Secondary)										
*Strain in./in.	Proportional Limit	ϵ_1									
		ϵ_2									
		ϵ_{45}									
	Ultimate	ϵ_1	0.00634	0.00775	0.00771	0.00731	0.00643			0.00710	
		ϵ_2	0.00015	0.00036	0.00008	0.00029	0.00012			0.00020	
		ϵ_{45}									
Specimen Width (in.)			0.749	0.745	0.740	0.742	0.750			0.746	
Specimen Thick. (in.)			0.038	0.037	0.036	0.036	0.037			0.037	

Strain Gage No. EA-03-250BF-350

Extensometer

Properties Based on Nominal ☐; Actual ☒

Filament Count -- /in. Void Content 0 % Ply Thick. 0.0091 in.

Fil. Vol. Fract. 0.5837 Resin Wt. Fract. 0.____ Lam. Density 0.0559 lb/in.^{3}

Laminate: Tape or Matrix Design broadgoods-M. L. Manuf. Fiberite

Balance Ply N/A Cure Spec SwRI S3-303

Organization: SwRI

Comments: Static stress/strain tests; loading rate = 0.0125 in./in./min
(1) Longitudinal stress at transverse strain knee.

*Indicates Strain Measurement by Resistance Strain Gages.

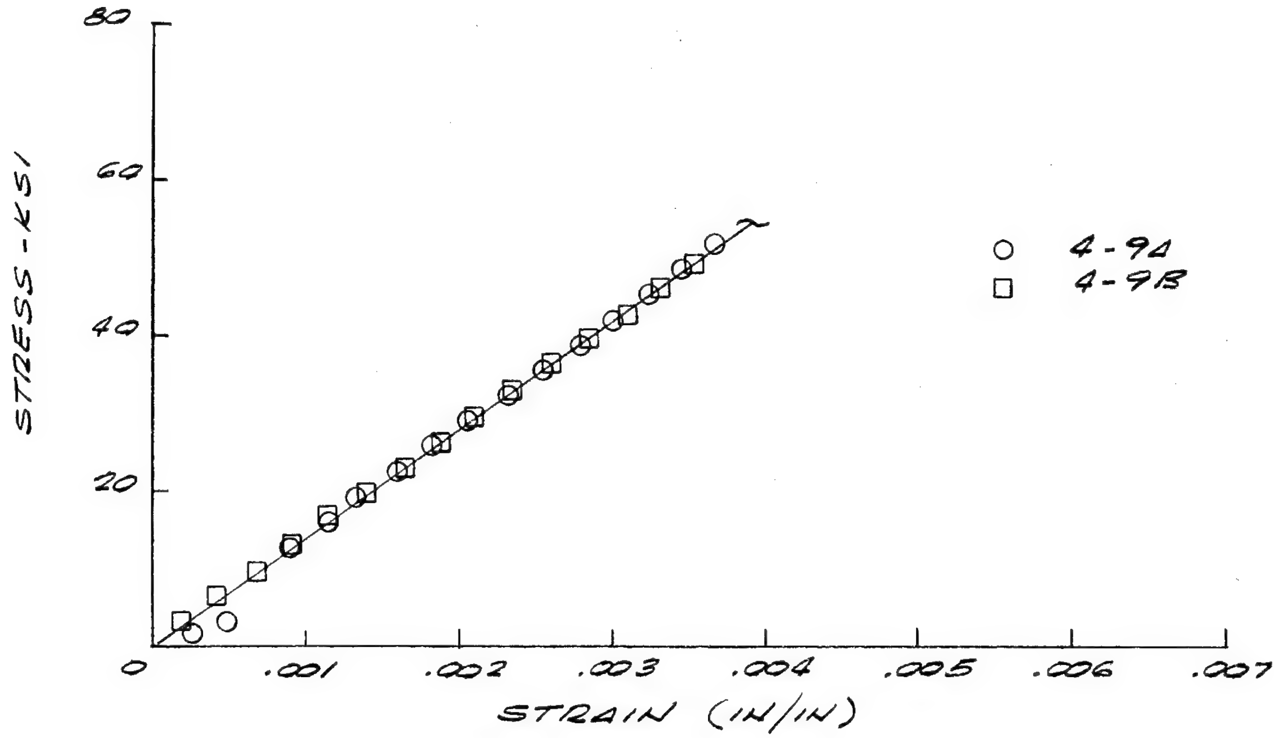


FIGURE II.10. STRESS VS LONGITUDINAL STRAIN, 4-9A AND 4-9B (EXTENSOMETER)

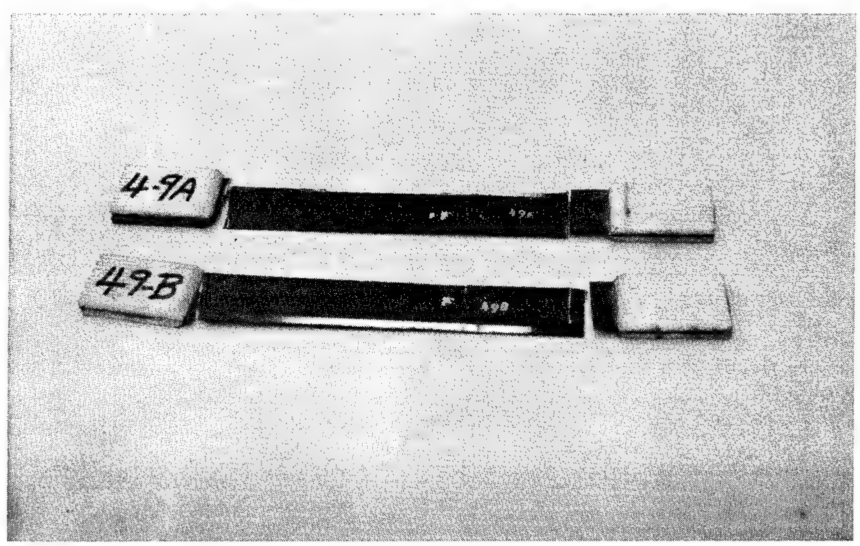


FIGURE II.11. UNIAXIAL TENSILE SPECIMENS 4-9A, B AFTER FAILURE, $[90/0]_S$

TABLE II. 5

STATIC TENSION, C-27

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS - Treated   Lam. Orient. $[90/0]_S$

Matrix - ERL 2256   No. of Plies 4

Load Orient. -

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☒, Comp ☐, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: Standard Tensile, SwRI 03-401

Soak at Temp: n/a °F for - hr   Test Temp. RT °F

Property			Panel No.	C-27							Ave	S. D.
			Spec. Ident.									
Stress (ksi)	F_{pl}			4-9A	4-9B							
	F__											
	F__											
	F__											
	F_{ult}			68.00	71.49						69.74	2.47
Modulus $E, G \times 10^{-6}$	E or G (Primary)			13.80	13.66						13.73	0.099
	E' or G' (Secondary)											
Strain in./in.	Proportional Limit	ϵ_1										
		ϵ_2										
		ϵ_{45}										
	Ultimate	ϵ_1		0.00584	0.00600						0.00592	
		ϵ_2										
		ϵ_{45}										
Specimen Width (in.)				1.000	1.000						1.000	
Specimen Thick. (in.)				0.032	0.031						0.0315	

Strain Gage No. MM EA 03-250 BF-350
Extensometer

Properties Based on Nominal ☐; Actual ☒

Filament Count -- /in. Void Content 3.22 % Ply Thick. 0.008 in.

Fil. Vol. Fract. 0. 640 Resin Wt. Fract. 0. 271 Lam. Density 0.0570 lb/in.^{3}

Laminate: Tape or Matrix Design broadgoods-meter length Manuf. Fiberite

Balance Ply n/a Cure Spec SwRI S3-303

Organization : SwRI

Comments:

*Indicates Strain Measurement by Resistance Strain Gages.

TABLE II.6

STATIC TENSION GAGE COMPARISON AND BENDING MEASUREMENT, C-57

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS   Lam. Orient. $[0/90_2/0]_{3T}$

Matrix - ERLA 2256   No. of Plies 12

Load Orient. 0

Balance Ply Added: Yes ☐ No ☐

Loading Type: Tension ☒, Comp ☐, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: SwRI Universal Tensile Compression Specimen ϕ

Soak at Temp: - °F for - hr   Test Temp. RT °F

Property		Panel No.	C-57						Avg	C.F.θ	Avg C.F.
		Spec. Ident.**	C-57Z(a)	C-57Z(b)							
Stress (ksi)	$F_{pl B\text{-}avg}$		26.410	35.556					30.983		
	$F_{pl A\text{-}avg}$		-	15.377							
	F__										
	F__										
	F_{ult}		67.682	67.682							
Modulus $E, Gx10^{-6}$	E_B Avg		10.830	9.891						1.095	1.090
	E_C Avg		11.340	10.460						1.084	
* Strain in./in.	Proportional Limit B-avg	ϵ_1	0.002404	0.003616							
		ϵ_2									
		ϵ_{45}									
	Ultimate Avg	ϵ_1	0.005993	0.006520							
		ϵ_2									
		ϵ_{45}									
Specimen Width (in.)			0.497								
Specimen Thick. (in.)			0.107								

Strain Gage No. (a)MM EA-03-250BF-350
" " " (b)MM EP-08-015DJ-120

Properties Based on Nominal ☐; Actual ☒

Filament Count - /in.   Void Content 0.92 %   Ply Thick. 0.0088 in.

Fil. Vol. Fract. 0.5661   Resin Wt. Fract. 0.____   Lam. Density 0.0551 lb/in.^{3}

Laminate: Tape or Matrix Design broadgoods-M.L. tow   Manuf. Fiberite

Balance Ply n/a   Cure Spec SwRI S3-303

Organization: SwRI

Comments: **One specimen C-57Z, (a) is stress-strain data based on MM-03-250BF-350 strain gages on the faces (back-to-back) and (b) is stress-strain data based on EP-08-015DJ-120 strain gages on opposite edges; see curves

*Indicates Strain Measurement by Resistance Strain Gages.

θCorrection factor = $\frac{(a)}{(b)}$ for moduli

ϕSee Dwg 03-2776-01-3

(a) 350 OHM $\frac{1}{4}$-INCH FACE GAGES WITH 03 TEMP. COMPENSATION

F_{ULT} = 67,682 PSI
ϵ_{U_1} = 0.005790 (0.005772 COR.) IN./IN.
ϵ_{U_2} = 0.006195 (0.006179 COR.) IN./IN.
$\epsilon_{U_{AVG}}$ = 0.005993 (0.005976 COR.) IN./IN.
E_{C_1} = 11.726 × 10^6 PSI
E_{C_2} = 10.954 × 10^6 PSI
$E_{C_{AVG}}$ = 11.340 × 10^6 PSI

$F_{PL_{B1}}$ = 35,392 PSI
$\epsilon_{PL_{B1}}$ = 0.003114 IN./IN.
$F_{PL_{B2}}$ = 17,427 PSI
$\epsilon_{PL_{B2}}$ = 0.001693 IN./IN.
$F_{PL_{BAVG}}$ = 26,410 PSI
$\epsilon_{PL_{BAVG}}$ = 0.002404 IN./IN.
E_{B_1} = 11.365 × 10^6 PSI
E_{B_2} = 10.294 × 10^6 PSI
$E_{B_{AVG}}$ = 10.830 × 10^6 PSI

$[0/90]_S$

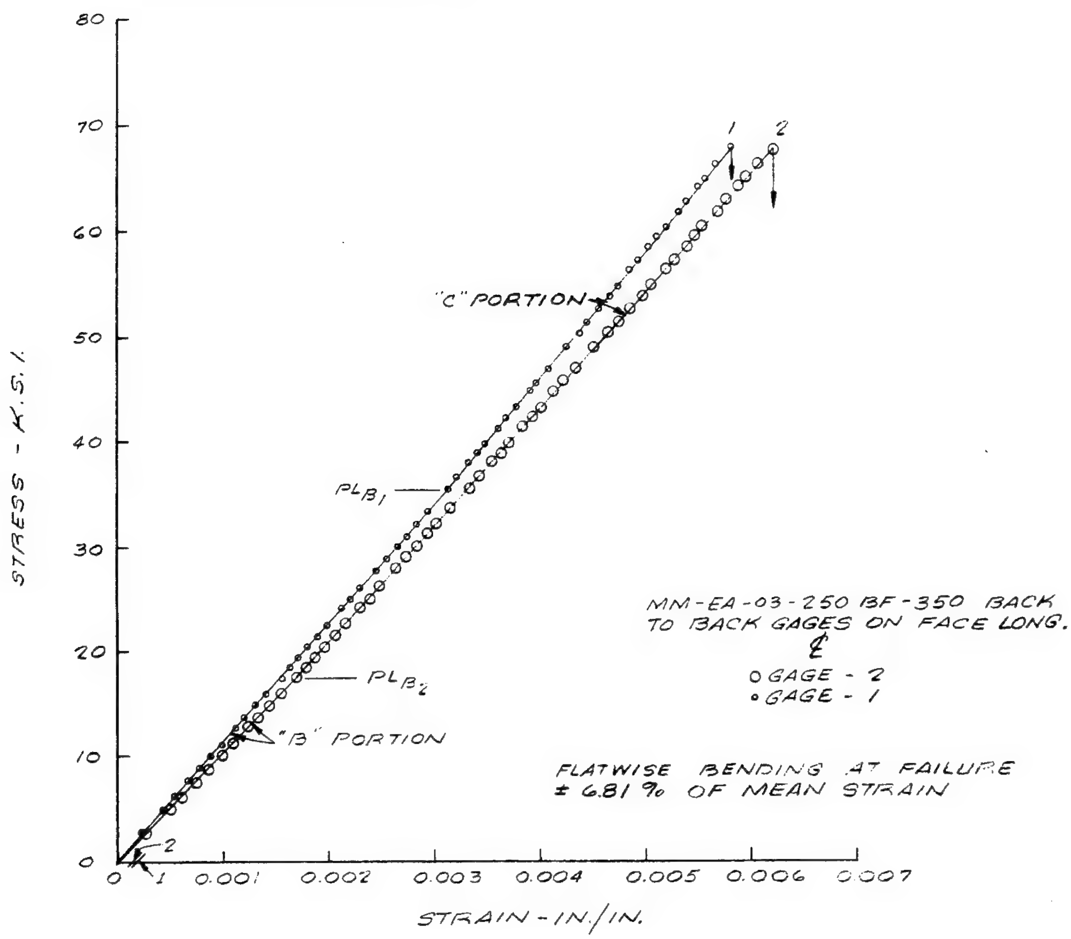


FIGURE II.12 STATIC TENSION STRESS VS STRAIN FOR STRAIN GAGE COMPARISON AND BENDING MEASUREMENT, C57Z

(b) 120 OHM $\frac{1}{16}$-INCH EDGE GAGES WITH 08 TEMP. COMPENSATION

F_{ULT} = 67,682 PSI

ϵ_{U_1} = 0.006719 (0.006675) IN./IN.

ϵ_{U_2} = 0.006322 (0.006278) IN./IN.

$\epsilon_{U_{AVG.}}$ = 0.006520 (0.006476) IN./IN.

E_{C_1} = 10.140×10^6 PSI

E_{C_2} = 10.781×10^6 PSI

$E_{C_{AVG.}}$ = 10.460×10^6 PSI

[0/90]$_s$

$F_{PL_{B1}}$ = 35,524 PSI

$F_{PL_{B2}}$ = 35,589 PSI

$F_{PL_{AVG.}}$ = 35,556 PSI

$\epsilon_{PL_{B1}}$ = 0.003731 (0.003713) IN./IN.

$\epsilon_{PL_{B2}}$ = 0.003502 (0.003484) IN./IN.

$\epsilon_{PL_{B\text{-}AVG.}}$ = 0.003616 (0.003598) IN./IN.

E_{B1} = 9.567×10^6 PSI

E_{B2} = 10.215×10^6 PSI

$E_{B\text{-}AVG.}$ = 9.891×10^6 PSI

$F_{PL_{A1}}$ = 15,908 PSI

$F_{PL_{A2}}$ = 14,846 PSI

$F_{PL_{A\text{-}AVG.}}$ = 15,377 PSI

$\epsilon_{PL_{A1}}$ = 0.001725 (0.001728) IN./IN.

$\epsilon_{PL_{A2}}$ = 0.001559 (0.001575) IN./IN.

$\epsilon_{PL_{A\text{-}AVG.}}$ = 0.001642 (0.001652) IN./IN.

E_{A1} = 9.206×10^6 PSI

E_{A2} = 9.426×10^6 PSI

$E_{A\text{-}AVG.}$ = 9.316×10^6 PSI

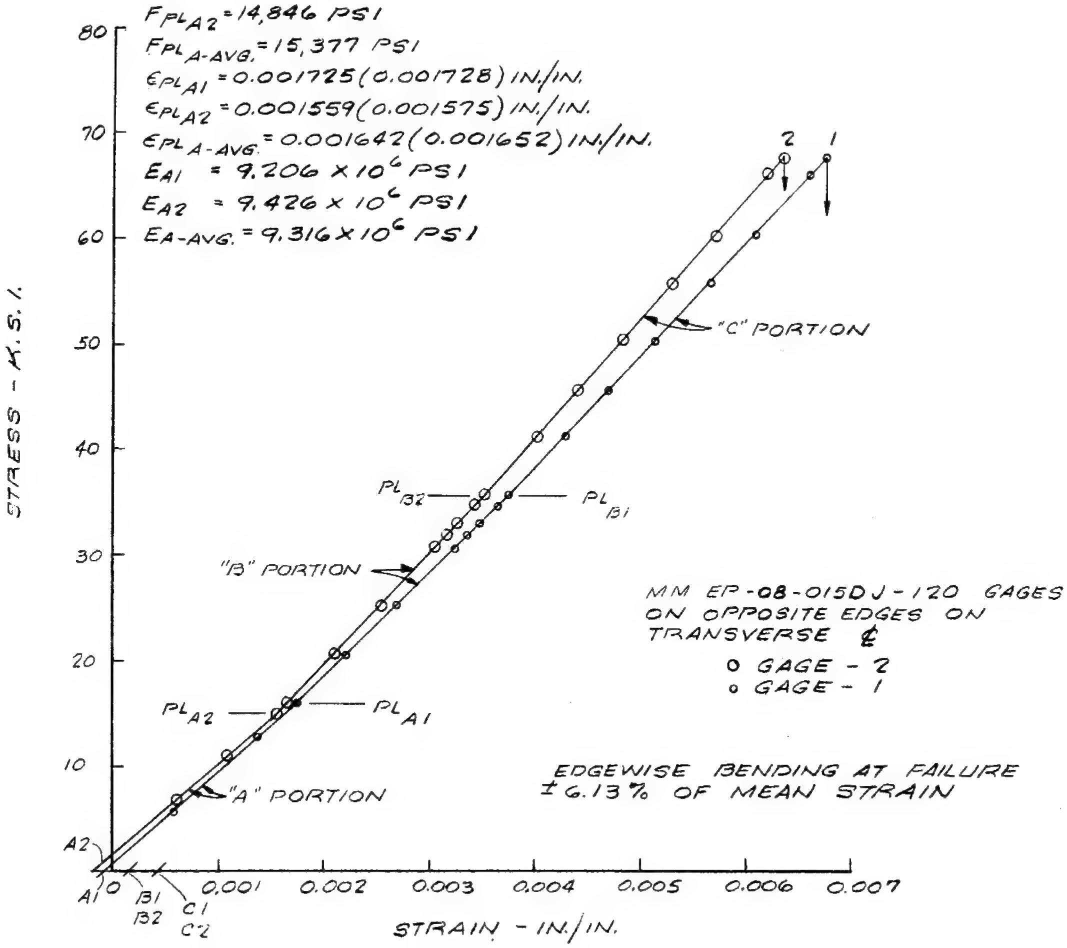


FIGURE II.12 (Cont'd.)

TABLE II. 7

STATIC TENSION, C-57

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtaulds HTS   Lam. Orient. $[0/90_2/0]_{3T}$

Matrix - ERL-2256   No. of Plies 12

Load Orient. 0

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☒, Comp ☐ Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐ , Transverse Flexure ☐

Type Test Specimen: SwRI 03-401

Soak at Temp: ______ °F for ______ hr   Test Temp. RT °F

Property		Panel No.	C-57								
		Spec. Ident.	T-57J	T-57K	T-57L					Ave	S.D.
Stress (ksi) or Poisson's Ratio	$^{(1)}F'_{pl}$		48.100	--	57.100					52.600	
	F__										
	F__										
	ν		0.0789	0.0684	0.0840					0.0771	
	F_{ult}		72.972	65.312	68.705					68.996	
Modulus $E, G \times 10^{-6}$	E or G (Primary)		12.002	12.231	11.990					12.074	
	E' or G' (Secondary)										
*Strain in./in.	Proportional Limit (Transverse)	ϵ_1	0.00405	--	0.00475					0.00440	
		ϵ_2	0.00031	--	0.00039					0.00035	
		ϵ_{45}									
	Ultimate	ϵ_1	0.00600	0.00535	0.00572					0.00569	
		ϵ_2	0.00041	0.00037	0.00041					0.00040	
		ϵ_{45}									
Specimen Width (in.)			0.753	0.750	0.748					0.750	
Specimen Thick. (in.)			0.106	0.106	0.106					0.106	

Strain Gage No. MM 03-250BF-350   Properties Based on

Extensometer B. Dualrange TSM-D-1047   Nominal ☐; Actual ☒

Filament Count -- /in, Void Content 0.92 % Ply Thick. 0.0088 in.

Fil. Vol. Fract. 0.5661 Resin Wt. Fract. 0. -- Lam. Density 0.0551 lb/in.^{3}

Laminate: Tape or Matrix Design Breadgoods-M. L. Tow   Manuf. Fiberite

Balance Ply N/A   Cure Spec SwRI 03-303

Organization: SwRI

Comments: (1) Longitudinal stress at transverse strain knee (see curves)

*Indicates Strain Measurement by Resistance Strain Gages.

TABLE II. 8

STATIC TENSION, C-60

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtaulds HTS   Lam. Orient. $[0/90_2/0]_{3T}$

Matrix - ERL-2256   No. of Plies 12

Load Orient. 0^o

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☒, Comp ☐, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: SwRI 03-401

Soak at Temp: ______ °F for ______ hr   Test Temp. RT °F

Property		Panel No.	C-60								
		Spec. Ident.	60-B	60-F	60-H	60-L	60-P			Ave	S.D.
Stress (ksi) or Poisson's Ratio		(1) F'_{pl}	41.100	40.750	40.000	--	40.250			40.525	
		F__									
		F__									
		ν	0.0457	0.0343	0.0233	--	0.0223			0.0314	
		F_{ult}	69.806	67.878	79.548	82.712	64.031			72.795	
Modulus $E, G \times 10^{-6}$		E or G (Primary)	10.146	10.443	10.430	11.330	10.328			10.535	
		E' or G' (Secondary)									
* Strain in./in.	Proportional Limit (Transverse)	ϵ_1	0.00405	0.00390	0.00395	--	0.00393			0.00395	
		ϵ_2	0.00018	0.00013	0.00090	--	0.00008			0.00072	
		ϵ_{45}									
	Ultimate	ϵ_1	0.00688	0.00650	0.00775	0.00743	0.00648			0.00700	
		ϵ_2	0.00024	0.00014	0.00005	--	0.00008				
		ϵ_{45}									
Specimen Width (in.)			0.753	0.749	0.750	0.750	0.749			0.750	
Specimen Thick. (in.)			0.121	0.119	0.118	0.118	0.115			0.118	

Strain Gage No. MM 03-250 BF-350   Properties Based on

Extensometer B. Dualrange TSM-D-1047   Nominal ☐; Actual ☒

Filament Count -- /in.   Void Content 0.680 %   Ply Thick. 0.00972 in.

Fil. Vol. Fract. 0.5166   Resin Wt. Fract. 0. --   Lam. Density 0.0542 lb/in.^{3}

Laminate: Tape or Matrix Design Broadgoods-M. L. Tow   Manuf. Fiberite

Balance Ply N/A   Cure Spec SwRI 03-303

Organization : SwRI

Comments: (1) Longitudinal stress at transverse strain knee (see curves)

*Indicates Strain Measurement by Resistance Strain Gages.

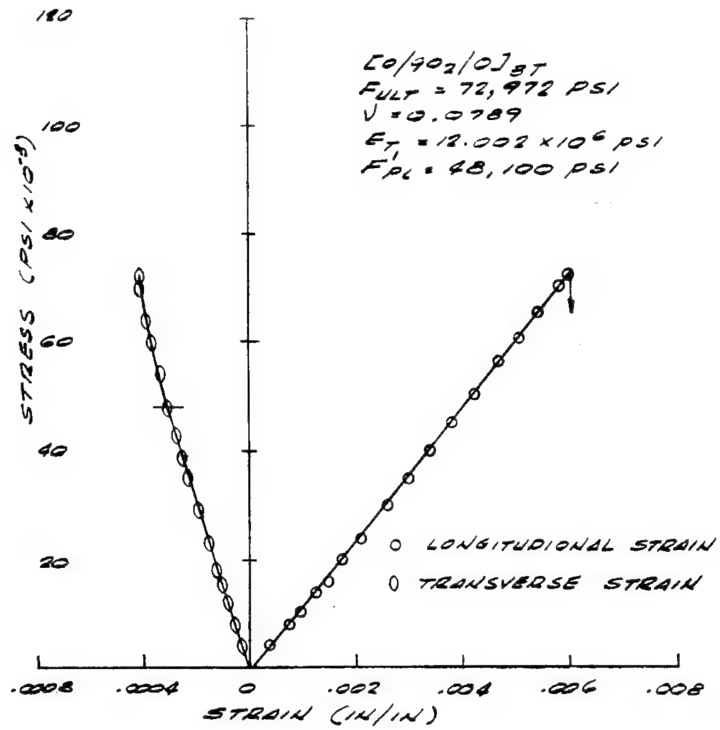


FIGURE II. 13. STRESS VS STRAIN, SPECIMEN T-57-J (Tension)

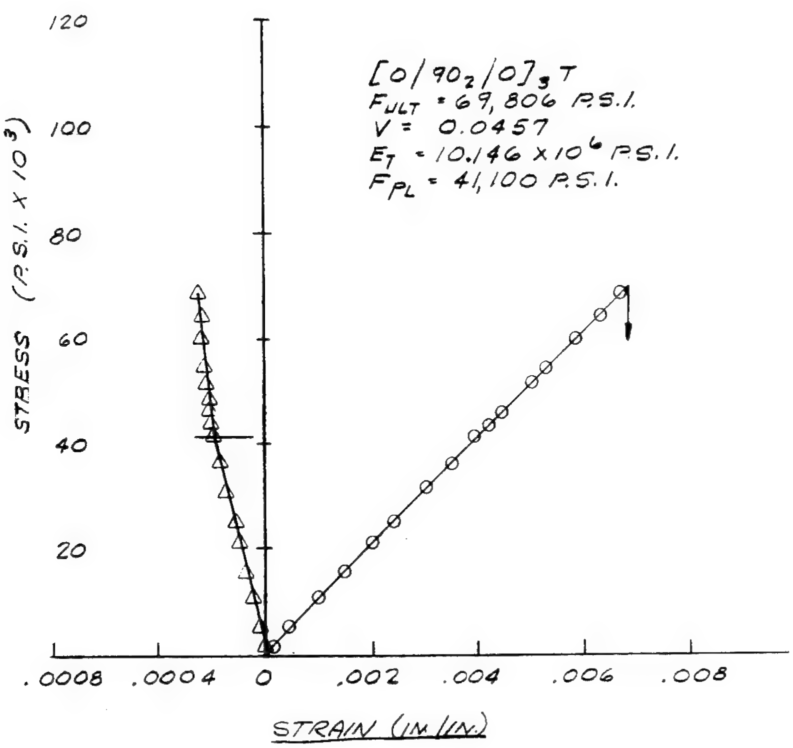


FIGURE II. 14. STRESS VS STRAIN, SPECIMEN SPECIMEN 60-B (Tension)

TABLE II.9

STATIC TENSION STRESS VS STRAIN, C-67

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS   Lam. Orient. $[0/90_2/0]_{3T}$

Matrix - ERLA 2256   No. of Plies 12

Load Orient. 0

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☒, Comp ☐, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐ , Transverse Flexure ☐

Type Test Specimen: SwRI Universal Tensile/Compression Specimen**

Soak at Temp: - °F for - hr Test Temp. RT °F

Property	Panel No. / Spec. Ident.	C-67 67-K	67-N	67-R					Ave	S.D.
ϕ Stress (ksi) or Poisson's ratio	F_{pl}									
	F___									
	ν	0.0307	0.0258	0.0339					0.0301	
	Fult (B)	65.019	64.504	58.397					62.640	
	Fult (L.C.)	65.505	65.986	60.146					63.879	
ϕ Modulus E, Gx10^{-6}	E (B)	13.337	13.232	10.640					12.403	
	E (L.C.)	12.920	12.471	12.811					12.733	
ϕ Strain in./in. Ext. & S.G. Ultimate (B)	ϵ_1	0.004875	0.004875	0.00550					0.005083	
	ϵ_2									
	ϵ_{45}									
Ultimate (L.C.)	ϵ_1	0.005070	0.005291	0.004695					0.005019	
	ϵ_2	-0.000151	-0.000134	-0.000159					-0.000148	
	ϵ_{45}									
Specimen Width (in.)		0.501	0.499	0.499						
Specimen Thick. (in.)		0.105	0.105	0.105						

Strain Gage No. EA-03-250BF-350   Properties Based on

Extensometer B. Dual Range TSMD-1047   Nominal ☐; Actual ☒

Filament Count - /in. Void Content 0.63 % Ply Thick. 0.0086 in.

Fil. Vol. Fract. 0.5634 Resin Wt. Fract. 0. - Lam. Density 0.0552 lb/in.^{3}

Laminate: Tape or Matrix Design broadgoods-M.L. tow Manuf. Fiberite

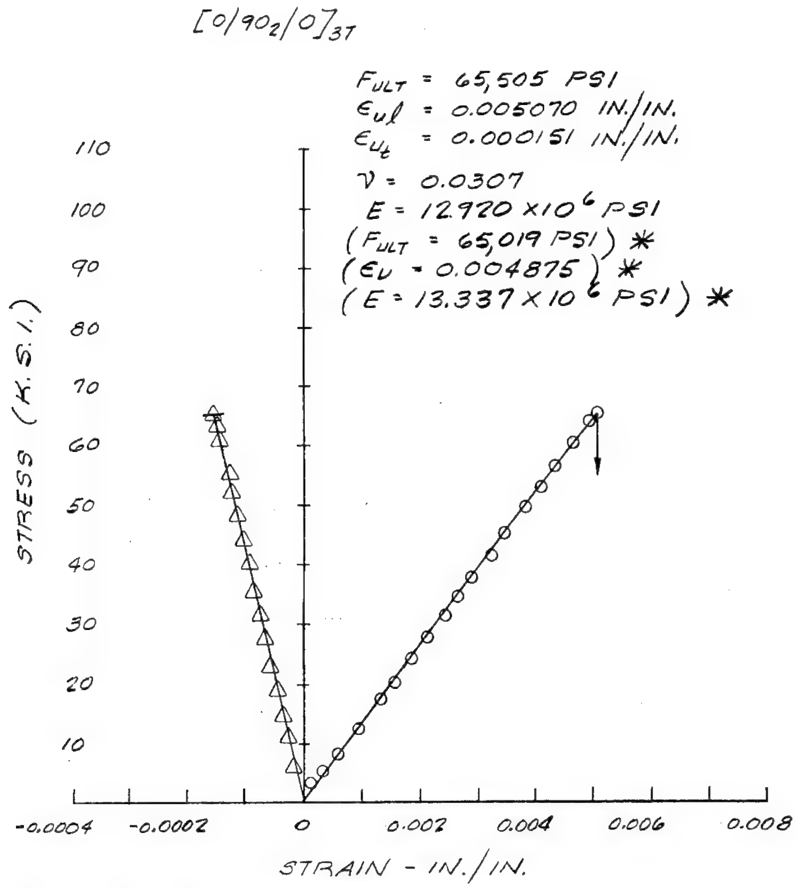
Balance Ply n/a Cure Spec SwRI S3-303

Organization : SwRI

Comments: *Ref SwRI Dwg 03-2776-01-3

ϕ(B)Baldwin direct reading or extensometer, (L.C.)Load cell or strain gage

*Indicates Strain Measurement by Resistance Strain Gages.



*Baldwin direct reading and/or extensometer values.

FIGURE II. 15. TENSION STRESS VS STRAIN, 67K

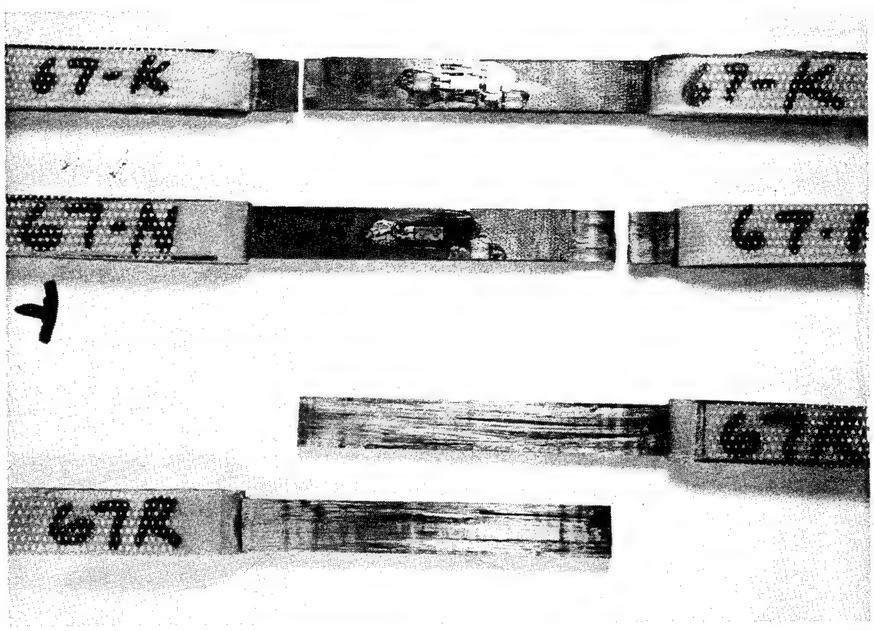


FIGURE II. 16. TENSILE SPECIMENS 67-K, N, R AFTER FAILURE, $[0/90_2/0]_{3T}$

APPENDIX II. 2

STATIC COMPRESSION

TABLE II.10

STATIC COMPRESSION, C-49

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS - Treated   Lam. Orient. $[0]_{12T}$

Matrix - ERL 2256   No. of Plies 12

Load Orient. 0^{o}

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☐, Comp ☒, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: SwRI Std Compression**

Soak at Temp: - °F for - hr Test Temp. RT °F

Property		Panel No.	C-49								
		Spec. Ident.		5-5B	5-5C					Ave	S. D.
Stress (ksi)	F_{pl}										
	F__										
	F__										
	F Initial										
	F_{ult} Subs.			131.5	134.5					133.0	B & C only
Modulus $E, G \times 10^{-6}$	(I) E or G (Primary)			21.31	22.44					21.88	B & C only
	E' or G' (Secondary)										
Strain in./in.	Proportional Limit	ϵ_1									
		ϵ_2									
		ϵ_{45}									
	Ultimate	ϵ_1		0.00617	0.00655					0.00636	B & C only
		ϵ_2									
		ϵ_{45}									
Specimen Width (in.)				0.502	0.501						
Specimen Thick. (in.)				0.100	0.100						

Strain Gage No. EP-08-015 DT-120   Properties Based on

Extensometer Model PC-7M Compressometer   Nominal ☐; Actual ☒

Filament Count - /in. Void Content 3.39 % Ply Thick. 0.0083 in.

Fil. Vol. Fract. 0.6187 Resin Wt. Fract. 0.___ Lam. Density .0564 lb/in.^{3}

Laminate: Tape or Matrix Design broadgoods-meter length Manuf. Fiberite

Balance Ply n/a Cure Spec SwRI S3-303

Organization: SwRI

Comments: Note: Modulus values given are the average for both gages on each specimen.

**Reference SwRI Drawing 03-2776-01-3

*Indicates Strain Measurement by Resistance Strain Gages.

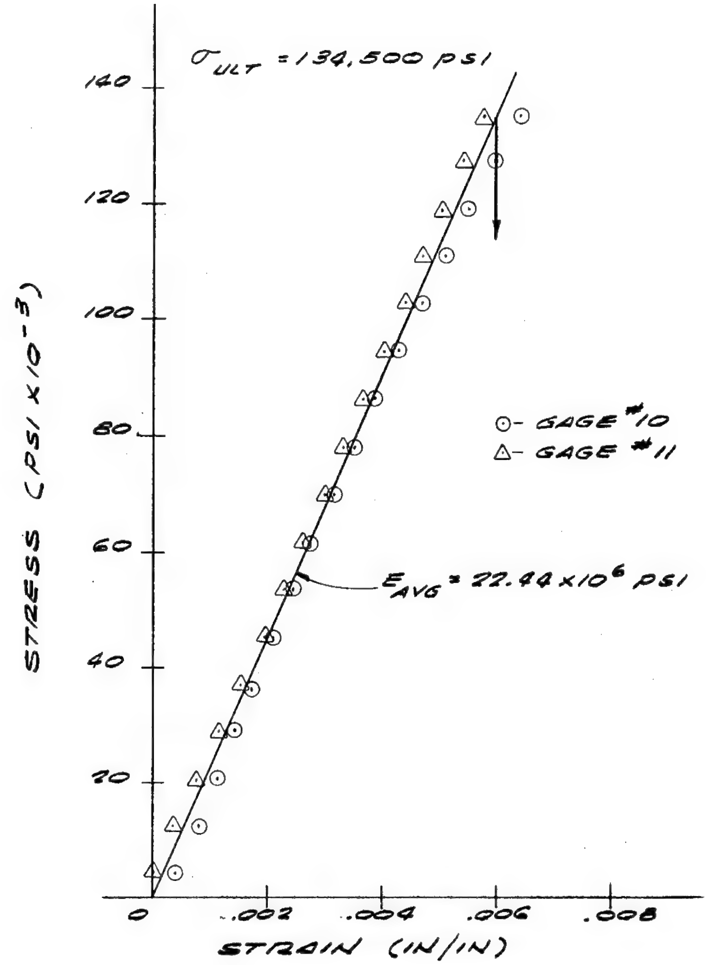


FIGURE II.17. STRESS VS STRAIN, SPECIMEN 5-5C (COMPRESSION)

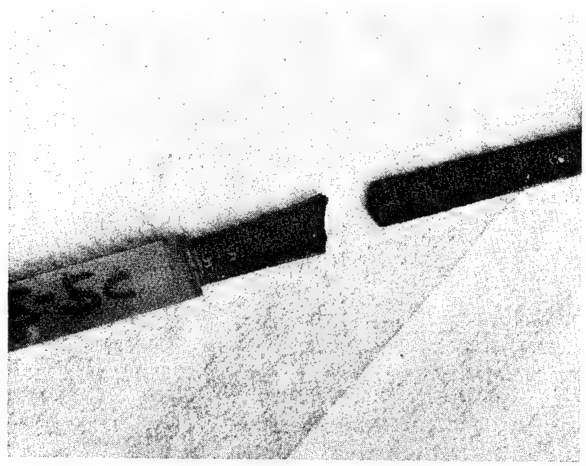


FIGURE II.18. UNIAXIAL COMPRESSION SPECIMEN 5-5C AFTER FAILURE, $[0]_{12T}$

TABLE II.11

STATIC COMPRESSION, C-68

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS Lam. Orient. $[90]_{12T}$

Matrix - ERL-2256 No. of Plies 12

Load Orient. 0°

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☐, Comp ☒, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: SwRI Standard Compression $^{\phi}$

Soak at Temp: ____ °F for ____ hr Test Temp. RT °F

Property		Panel No. / Spec. Ident.	C-68 / 68-D	68-E	68-F					Ave	S.D.
Stress (ksi)		F_{pl}	17.75	16.25	16.40					16.80	
		F__									
		F__									
		F__									
		F_{ult}	26.67	26.21	27.61					26.83	
Modulus $E, G \times 10^{-6}$		E or G (Primary)	1.18	1.02	1.12					1.11	
		E' or G' (Secondary)									
*Strain in./in.	Proportional Limit	ϵ_1	0.0150	0.0155*	0.0150**					0.0152	
		ϵ_2									
		ϵ_{45}									
	Ultimate	ϵ_1	0.0260	0.0296	0.0368					0.0308	
		ϵ_2									
		ϵ_{45}									
Specimen Width (in.)			0.500	0.497	0.500					0.499	
Specimen Thick. (in.)			0.114	0.114	0.113					0.1136	

Strain Gage No. MM EP08-015DJ-120 Properties Based on

Extensometer B. Compression PC7M(P)-1012 Nominal ☐; Actual ☒

Filament Count -- /in. Void Content 0.82 % Ply Thick. 0.00946 in.

Fil. Vol. Fract. 0.5639 Resin Wt. Fract. 0. -- Lam. Density 0.0551 lb/in.^{3}

Laminate: Tape or Matrix Design Broadgoods-M. L. Manuf. Fiberite

Balance Ply N/A Cure Spec SwRI S3-303

Organization: SwRI

Comments: * 0 Stress at 0.0010 in/in strain.
** 0 Stress at 0.0005 in/in strain
ϕ Reference SwRI Drawing 03-2776-01-3.

*Indicates Strain Measurement by Resistance Strain Gages.

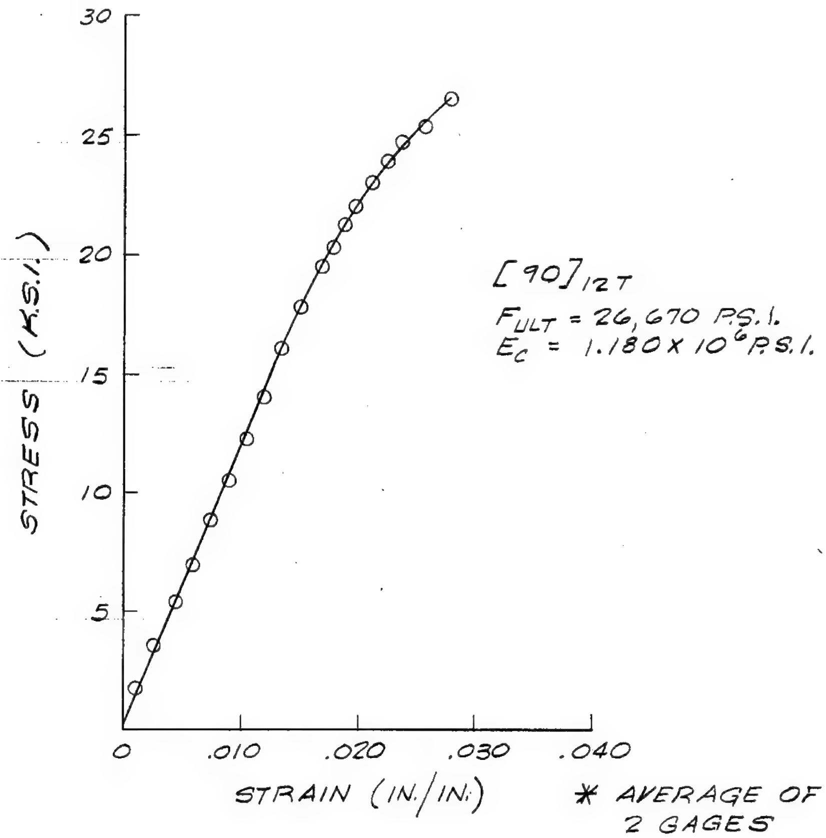


FIGURE II. 19. STRESS VS STRAIN,* SPECIMEN 68-D (Compression)

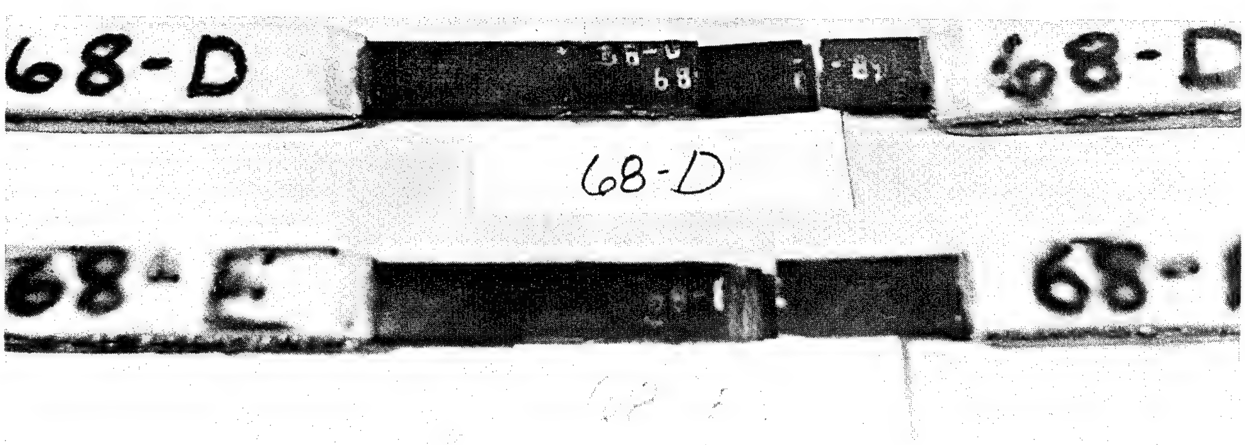


FIGURE II. 20. UNIAXIAL COMPRESSION SPECIMENS 68-D, E AFTER FAILURE, $[90]_{12T}$

TABLE II. 12

STATIC COMPRESSION, C-40

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS - Treated Lam. Orient. $[0/90_2/0]_{3T}$

Matrix - ERL 2256 No. of Plies 12

Load Orient. 0^o

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☐, Comp ☒, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: SwRI Standard Specimen**

Soak at Temp: - °F for - hr Test Temp. RT °F

Property			C-40								Ave	S. D.
	Spec. Ident.		5-13A	5-13C	5-13E							
Stress (ksi)	F_{pl}											
	F__											
	F__											
	F__											
	F_{ult}		64.96	86.28	78.24						76.49	
* Modulus $E, G\times10^{-6}$	E or G (Primary)		9.23	9.98	10.18						9.80	
	E' or G' (Secondary)											
* Strain in./in.	Proportional Limit	ϵ_1										
		ϵ_2										
		ϵ_{45}										
	Ultimate	ϵ_1	0.00706	0.00869	0.00795						0.00790	
		ϵ_2										
		ϵ_{45}										
Specimen Width (in.)			0.503	0.503	0.505							
Specimen Thick. (in.)			0.101	0.100	0.101							

Strain Gage No. EP-08-015 DJ-120 Properties Based on

Extensometer Model PC-7M Compressometer Nominal ☐; Actual ☒

Filament Count -- /in. Void Content 3.04 % Ply Thick. 0.0081 in.

Fil. Vol. Fract. 0.5571 Resin Wt. Fract. 0.____ Lam. Density .0552 lb/in.^{3}

Laminate: Tape or Matrix Design broadgoods-meter length Manuf. Fiberite

Balance Ply n/a Cure Spec SwRI S3-303

Organization: SwRI

Comments: **Reference SwRI Drawing 03-2776-01-3

*Indicates Strain Measurement by Resistance Strain Gages.

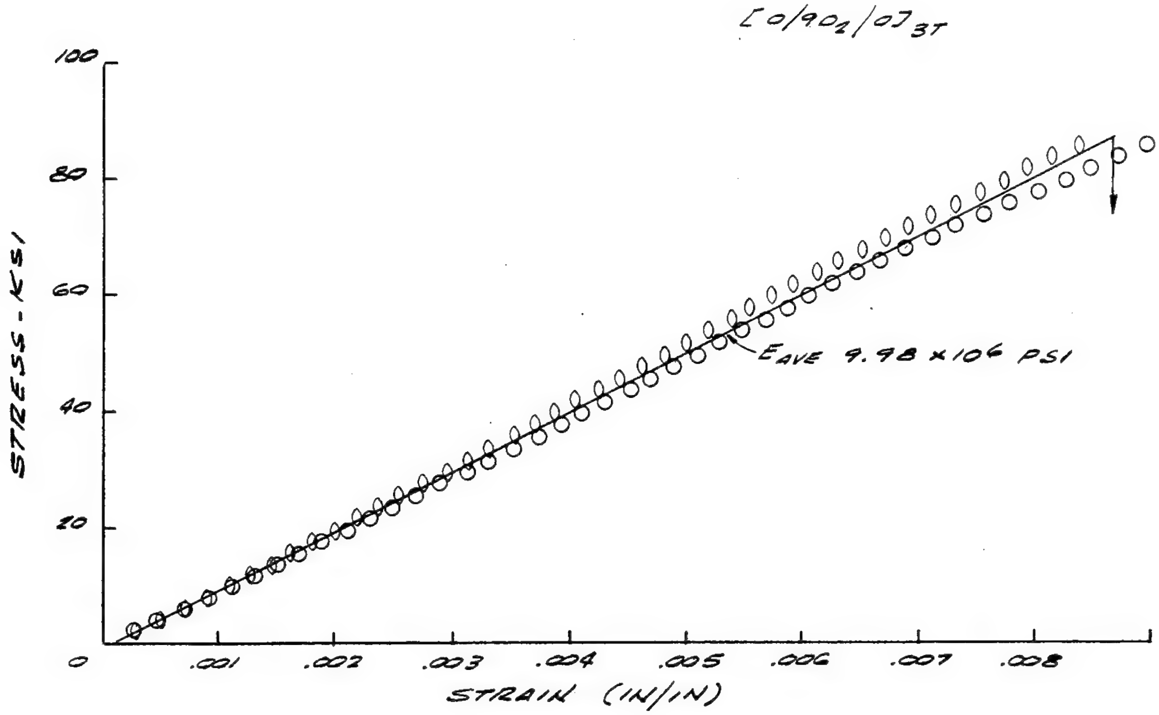


FIGURE II. 21. STRESS VS STRAIN, 5-13C (COMPRESSION)

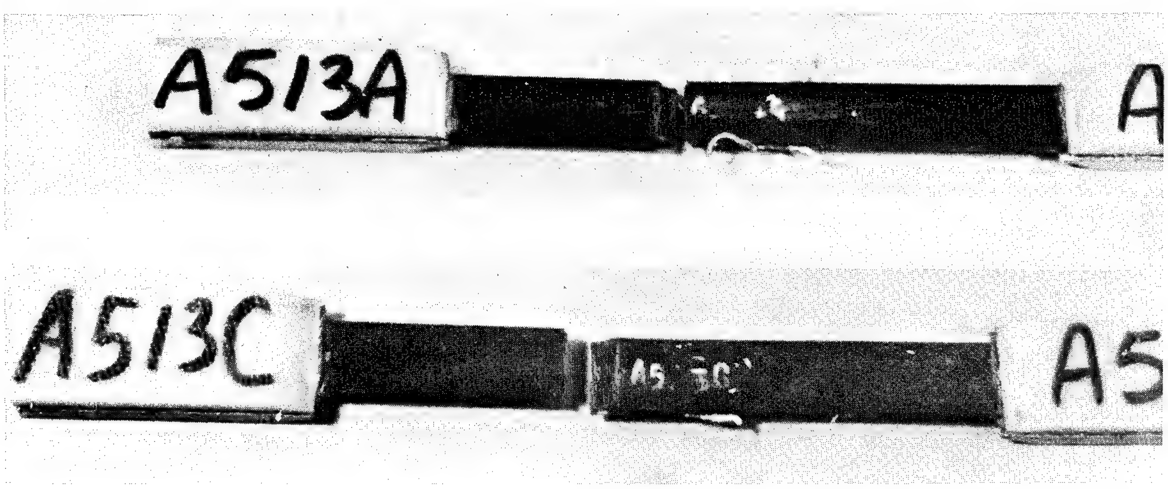


FIGURE II. 22. UNIAXIAL COMPRESSION SPECIMENS A5-13A, C AFTER FAILURE, $[0/90_2/0]_{3T}$

TABLE II. 13

STATIC COMPRESSION, C-57

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS   Lam. Orient. $[0/90_2/0]_{3T}$

Matrix - ERL 2256   No. of Plies 12

Load Orient. 0^o

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☐, Comp ☒, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: SwRI Standard Compression (UT/C)*

Soak at Temp: ______ °F for ______ hr   Test Temp. RT °F

Property		Panel No.	C-57								Ave	S.D.
		Spec. Ident.	57-C	57-U	57-DD							
Stress (ksi)	F_{pl}											
	F__											
	F__											
	F__											
	F_{ult}		80.49	77.36	84.39						80.25	
Modulus $E, Gx10^{-6}$	E or G (Primary)		8.81	9.71	8.90						9.14	
	E' or G' (Secondary)											
*Strain in./in.	Proportional Limit	ϵ_1										
		ϵ_2										
		ϵ_{45}										
	Ultimate	ϵ_1										
		ϵ_2										
		ϵ_{45}										
Specimen Width (in.)			0.497	0.499	0.495						0.497	
Specimen Thick. (in.)			0.106	0.105	0.107						0.106	

Strain Gage No. MM EP08-015DJ-120   Properties Based on

Extensometer Baldwin Compressometer PC7M(P)1012   Nominal ☐; Actual ☒

Filament Count -- /in. Void Content 0.92 % Ply Thick. 0.0088 in.

Fil. Vol. Fract. 0.5661 Resin Wt. Fract. 0. -- Lam. Density 0.0551 lb/in.^{3}

Laminate: Tape or Matrix Design Broadgoods-M. L. Tow Manuf. Fiberite

Balance Ply N/A Cure Spec SwRI 5-3-303

Organization: SwRI

Comments: *Reference SwRI Drawing 03-2776-01-3.

*Indicates Strain Measurement by Resistance Strain Gages.

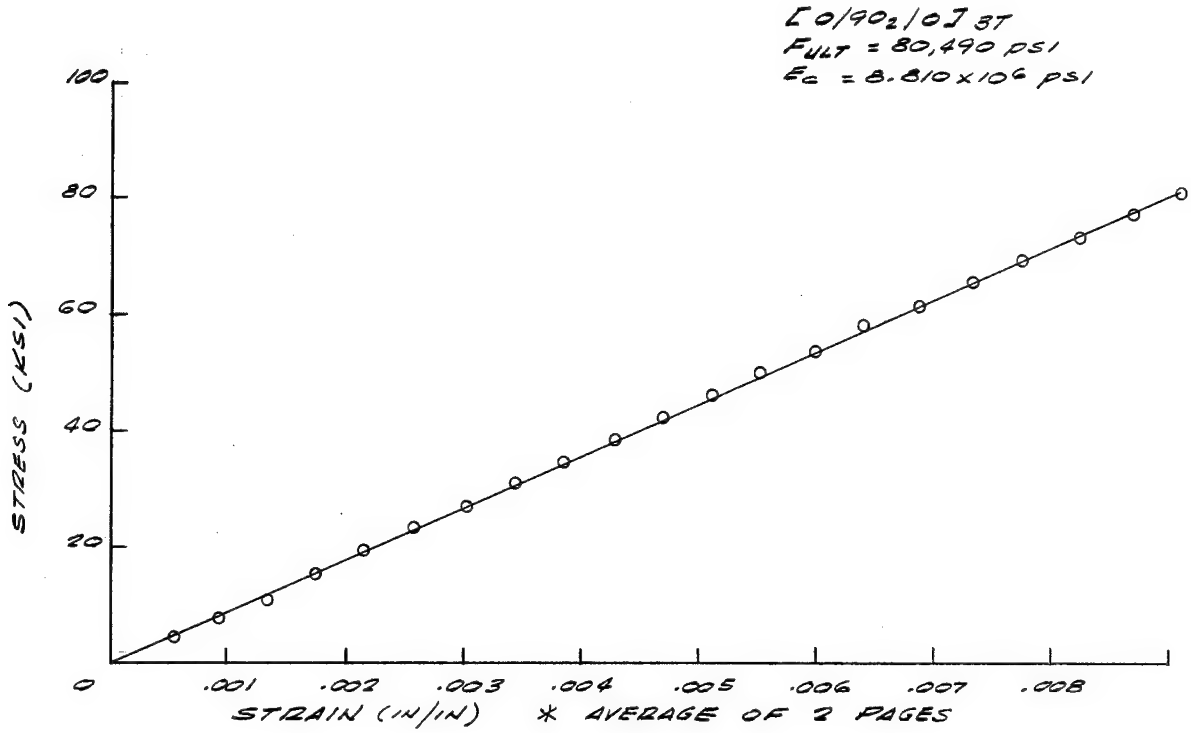


FIGURE II. 23. STRESS VS STRAIN*, SPECIMEN 57-C (Compression)

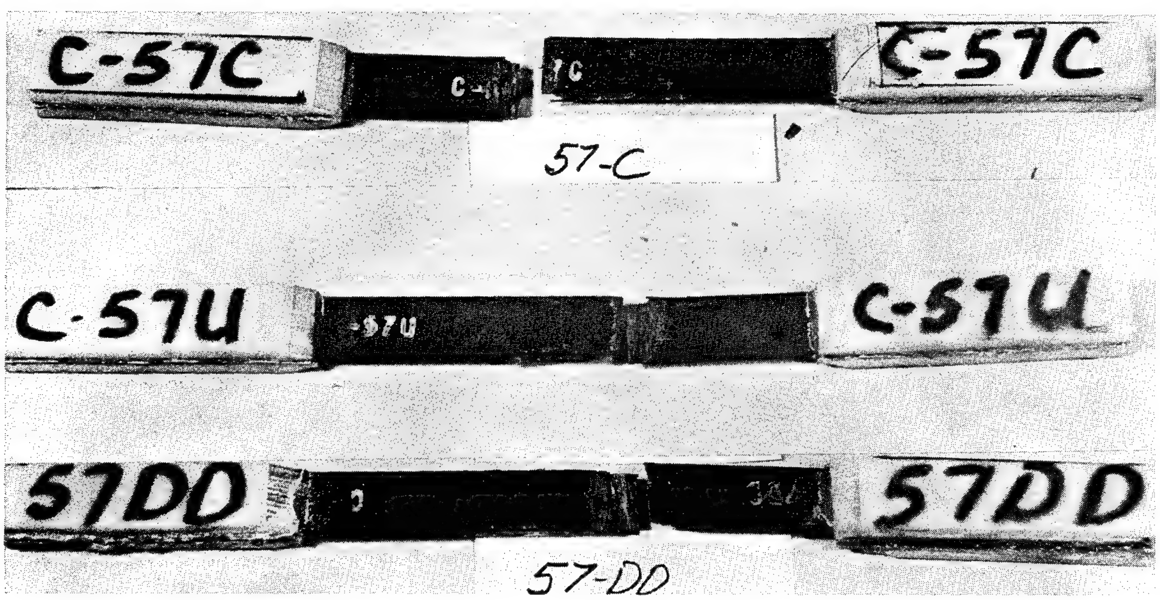


FIGURE II. 24. UNIAXIAL COMPRESSION SPECIMENS 57-C, U, DD AFTER FAILURE, $[0/90_2/0]_{3T}$

TABLE II. 14

STATIC COMPRESSION, C-55

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS - Treated   Lam. Orient. $[90/0_2/90]_{3T}$

Matrix - ERL 2256   No. of Plies 12

Load Orient. 90^o

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☐, Comp ☒, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: Std. Straight Sided**

Soak at Temp: n/a °F for - hr   Test Temp. RT °F

Property			C-55								
	Spec. Ident.		4-17A	4-17B						Ave	S.D.
Stress (ksi)	F_{pl}		36.10	30.20						33.15	
	F__										
	F__										
	F__										
	F_{ult}		62.19	35.82 ϕ						62.19	
Modulus $E, G \times 10^{-6}$	E or G (Primary)		10.219	11.875						11.047	
	E' or G' (Secondary)										
Strain in./in.	Proportional Limit	ϵ_1									
		ϵ_2									
		ϵ_{45}									
	Ultimate	ϵ_1	0.0070	0.0034						0.0052	
		ϵ_2									
		ϵ_{45}									
Specimen Width (in.)			0.499	0.497						0.498	
Specimen Thick. (in.)			0.0999	0.1000						0.09995	

Strain Gage No.   Properties Based on

Extensometer Model PC-7M Compressometer   Nominal ☐; Actual ☒

Filament Count - /in. Void Content 3.16 % Ply Thick. .00832 in.

Fil. Vol. Fract. 0.570 Resin Wt. Fract. 0.____ Lam. Density .0554 lb/in.^{3}

Laminate: Tape or Matrix Design broadgoods-meter length Manuf. Fiberite

Balance Ply n/a Cure Spec SwRI S3-303

Organization: SwRI

Comments: **Reference SwRI Drawing 03-2776-01-3
ϕ Ends not flat and parallel within tolerance, do not use value

*Indicates Strain Measurement by Resistance Strain Gages.

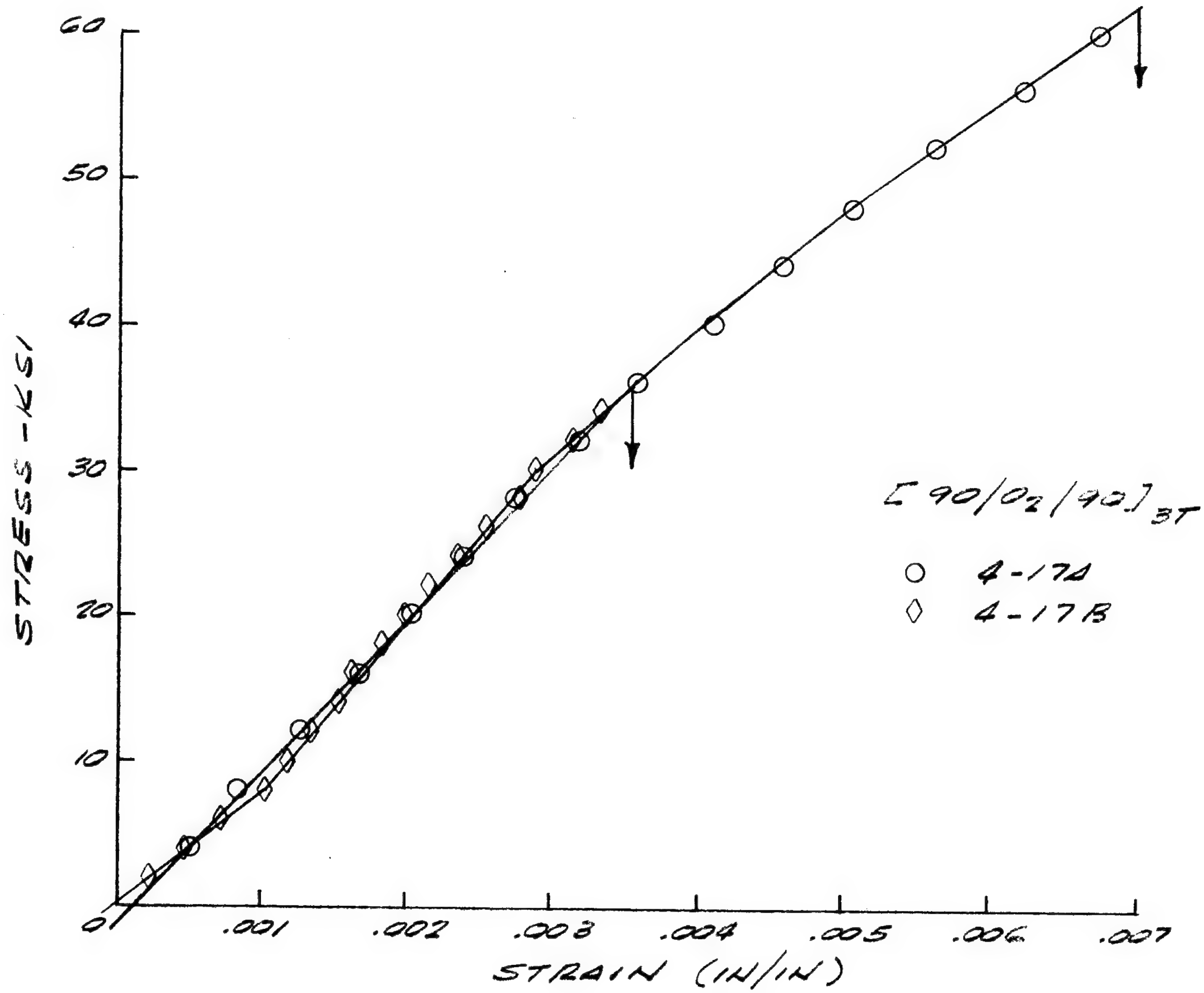


FIGURE II.25 STRESS VS LONGITUDINAL STRAIN, 4-17A AND 4-17B (COMPRESSION)

APPENDIX II. 3

INITIAL/SUBSEQUENT TENSION TESTS

TABLE II. 15

INITIAL/SUBSEQUENT TENSION LOAD TESTS, C-64

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS - Treated   Lam. Orient. $[0/90]_S$

Matrix - ERL 2256   No. of Plies 4

Load Orient. 0^o

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☒, Comp ☐, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: Standard Straight Sided, SwRI 03-401

Soak at Temp: - °F for - hr   Test Temp. RT °F

Property	Panel No. / Spec. Ident.	C-64 64A	64C	64D	64G	64K	64N		Ave	S. D.	
Stress (ksi)	(1) F_{pl}	43.00	47.30		53.00	54.1	46.3		48.74		
	$F_{.80}$ I	-	64.52	62.00	69.44	73.14	70.45		67.91		(77.7% F_{TU})
	ν_I	0.0156	0.045		0	0.0193	0.0466		0.0253		
	ν_S	-	0.023		0	0.0061	0.0244		0.0134		
	F_{ult} S	60.46	81.08	88.17	73.40	88.58	94.36		81.01	12.39	
Modulus $E, G \times 10^{-6}$	E or G Initial	11.32	11.49	10.75	12.14	12.47	11.86		11.67	0.66	
	E' or G' Subsequent	-	11.69	12.29	12.35	12.28	12.03		12.13	0.41	
*Strain in./in.	Proportional Limit ϵ_1										
	ϵ_2										
	ϵ_{45}										
	Ultimate ϵ_1	0.00551	0.00702	0.00600	0.00626	0.00731	0.00802		0.00668		
	ϵ_2	0.00006	-0.00018	0.00036	0.00054	-0.00008	-0.00018		0.00023		
	ϵ_{45}										
Specimen Width (in.)		0.750	0.750	0.754	0.750	0.750	0.746		0.750		
Specimen Thick. (in.)		0.037	0.037	0.037	0.036	0.035	0.036		0.0363		

Strain Gage No. EA-03-250BF-350   Properties Based on

Extensometer TSMD Dual Range   Nominal ☐; Actual ☒

Filament Count -- /in. Void Content 0 % Ply Thick. .0091 in.

Fil. Vol. Fract. 0.5837 Resin Wt. Fract. 0.___ Lam. Density .0559 lb/in.^{3}

Laminate: Tape or Matrix Design broadgoods-M. L. Manuf. Fiberite

Balance Ply N/A Cure Spec SwRI S3-303

Organization: SwRI

Comments: Note: Strain gages inoperative for specimen 64-D, specimen 64-A failed at initial loading.
(1) Longitudinal stress at transverse strain knee on initial loading.

*Indicates Strain Measurement by Resistance Strain Gages.

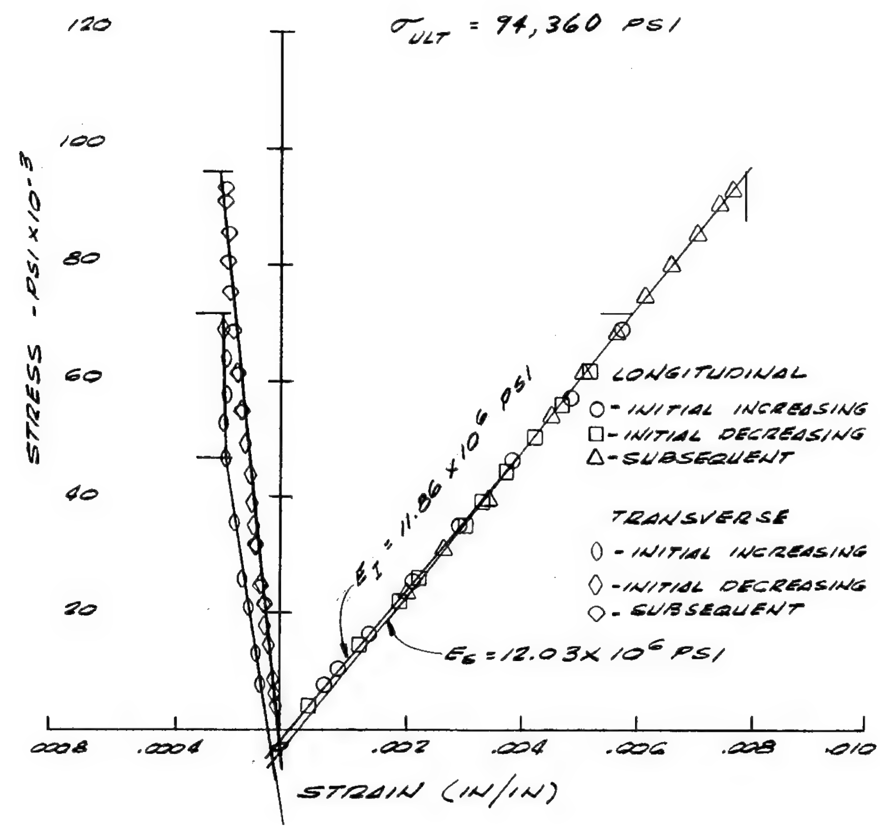


FIGURE II. 26. STRESS VS STRAIN, 64-N (INITIAL/ SUBSEQUENT LOAD TO FAILURE)

FIGURE II. 27. UNIAXIAL TENSION SPECIMEN 64C, K, N, AFTER FAILURE, $[0/90]_S$

TABLE II. 16

INITIAL LOAD (55% F_{ult}) TENSION, SECTION AND PHOTOMICROGRAPH, C-63

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS   Lam. Orient. $[0/90]_S$

Matrix - ERLA-2256   No. of Plies 4

Load Orient. 0

Balance Ply Added: Yes ☐ No ☒

Loading Type: Initial Tension ☒, Comp ☐, Shear ☐ Interlam. Shear ☐ Subsequent section and photomicrograph ☒

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: SwRI, 03-401 Specification

Soak at Temp: - °F for - hr Test Temp. RT °F

Property		Panel No.	C-63								Ave	%Fult
		Spec. Ident.	63P	63C								
Stress (ksi)	F_{pl}											
	F.533		41.394								42.932	55.3
	F.573			44.470								
	ν		0.0322	0.0233							0.0278	
	F_{ult}											
Modulus $E, G \times 10^{-6}$	E or G (Primary)		13.187	12.965							13.076	
	E' or G' (Secondary)											
* Strain in./in.	Initial Loading	ϵ_1	0.003139	0.003430							0.003284	
		ϵ_2	-0.000101	-0.000080							-0.000090	
		ϵ_{45}										
	Ultimate	ϵ_1										
		ϵ_2										
		ϵ_{45}										
Specimen Width (in.)			0.751	0.749								
Specimen Thick. (in.)			0.035	0.035								

Strain Gage No. MM EA-03-250BF-350   Properties Based on

Extensometer   Nominal ☐; Actual ☒

Filament Count - /in. Void Content 0.02 % Ply Thick. 0.0090 in.

Fil. Vol. Fract. 0.5877 Resin Wt. Fract. 0.____ Lam. Density 0.0560 lb/in.^{3}

Laminate: Tape or Matrix Design broadgoods-M. L. tow Manuf. Fiberite

Balance Ply n/a Cure Spec SwRI S3-303

Organization : SwRI

Comments:

*Indicates Strain Measurement by Resistance Strain Gages.

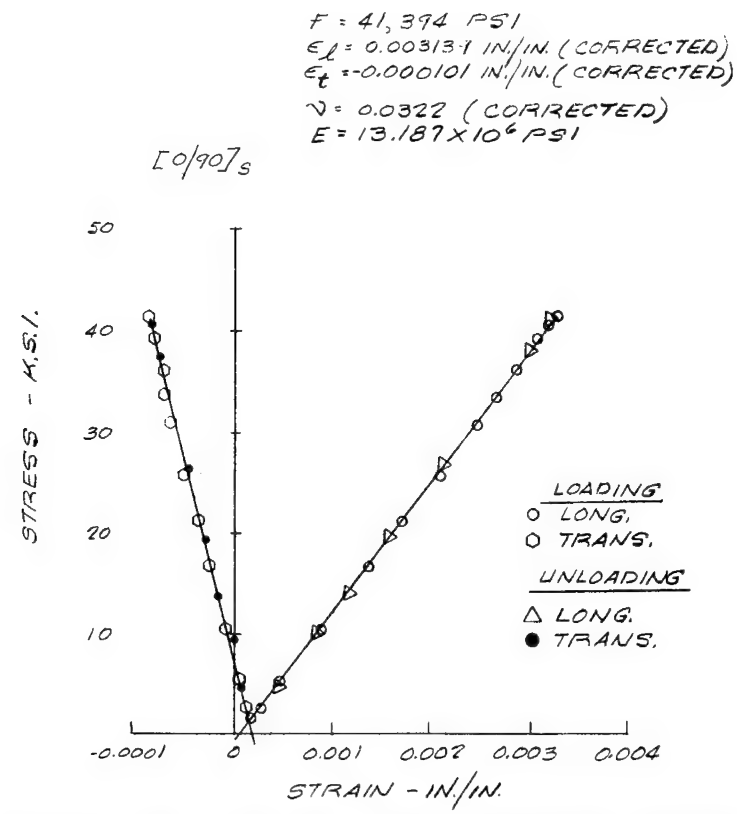
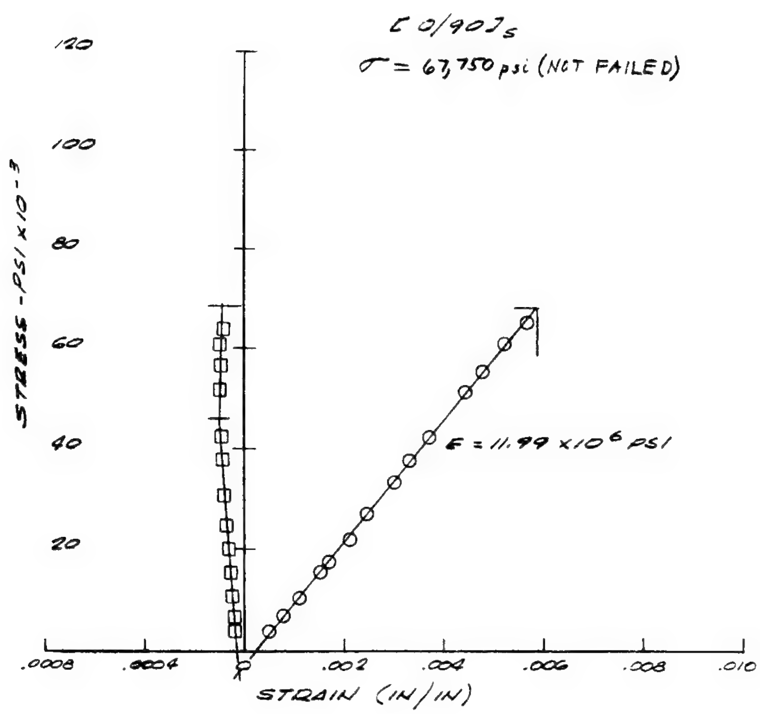


FIGURE 28. INITIAL LOAD TENSION STRESS VS STRAIN AND SECTION, 63P



II. 29. STRESS VS STRAIN, 64-M (TENSION)

TABLE II. 17

INITIAL LOAD TENSION FOR PHOTOMICROGRAPHS, C-64

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS - Treated Lam. Orient. $[0/90]_S$

Matrix - ERL 2256 No. of Plies 4

Load Orient. 0^o

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☒, Comp ☐, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: Standard Straight Sided, SwRI 03-401

Soak at Temp: - °F for - hr Test Temp. RT °F

Property		Panel No.	C-64									
		Spec. Ident.	64-F	64-M						Ave		
Stress (ksi)	(1) F_{pl}		48.5	45.7						47.10		
	$F_{.82}$			67.75						68.46		(78.3% F_{TU})
	$F_{.81}$		69.16									
	ν		0.052	0.025						0.0385		
	F_{ult}											
* Modulus $E, G \times 10^{-6}$	E or G (Primary)		11.28	11.99						11.64		
	E' or G' (Secondary)											
Strain in./in.	Proportional Limit	ϵ_1										
		ϵ_2										
		ϵ_{45}										
	Ultimate	ϵ_1										
		ϵ_2										
		ϵ_{45}										
Specimen Width (in.)			0.744	0.746								
Specimen Thick. (in.)			0.036	0.037								

Strain Gage No. EA-03-250BF-350
Extensometer
Properties Based on Nominal ☐; Actual ☒

Filament Count -- /in. Void Content 0 % Ply Thick. 0.0091 in.

Fil. Vol. Fract. 0.5837 Resin Wt. Fract. 0.___ Lam. Density 0.0559 lb/in.³

Laminate: Tape or Matrix Design broadgoods-M. L. Manuf. Fiberite

Balance Ply N/A Cure Spec SwRI S3-303

Organization: SwRI

Comments: Initial load to damage level; section and photomicrograph
(1) Longitudinal stress at transverse strain knee.

*Indicates Strain Measurement by Resistance Strain Gages.

TABLE II.18

INITIAL LOAD (83% F_{ult}) TENSION, SECTION AND PHOTOMICROGRAPH, C-63

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS — Lam. Orient. $[0/90]_S$

Matrix - ERLA 2256 — No. of Plies 4

Load Orient. 0

Balance Ply Added: Yes ☐ No ☒

Loading Type: Initial Tension ☒, Comp ☐, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐ Subsequent Section & Photomicrograph ☒

Type Test Specimen: SwRI 03-401

Soak at Temp: - °F for - hr Test Temp. RT °F

Property		Panel No.	C-63							Ave	% Fult
		Spec. Ident.	63-H	63-R							
Stress (ksi)		(1) F^{ϕ}_{pl}	48.135	61.572						49.854	
		Fpl	53.880	59.791						56.336	
		F0.839	65.190							64.523	83.05
		F0.822		63.856							
		ν	0.0728	0.0098						0.0413	
Modulus E, Gx10⁻⁶		E or G (Primary)	13.363	10.484						11.924	
		E' or G' (Secondary)									
* Strain in./in.	Proportional (1) Limit	ϵ_1	0.003597	0.004170						0.003884	
		ϵ_2	-0.000262	-0.00040						-0.000151	
	Proportional limit	ϵ_1	0.004032	0.004654						0.004343	
		ϵ_2	-0.000286	-0.000061						-0.000174	
	Initial Loading	ϵ_1	0.004996	0.004730						0.004863	
		ϵ_2	-0.000343	-0.000061						-0.000202	
Specimen Width (in.)			0.751	0.753							
Specimen Thick. (in.)			0.035	0.035							

Strain Gage No. MM EA 03-250BF-350 — Properties Based on

Extensometer — Nominal ☐; Actual ☒

Filament Count - /in. Void Content 0.02 % Ply Thick. 0.0090 in.

Fil. Vol. Fract. 0.5877 Resin Wt. Fract. 0.____ Lam. Density 0.0560 lb/in.³

Laminate: Tape or Matrix Design broadgoods - M.L. tow Manuf. Fiberite

Balance Ply n/a Cure Spec SwRI S3-303

Organization: SwRI

Comments: (1) Longitudinal stress at transverse strain knee

ϕ The 1st P.L. occurred at 26.870 ksi on the transverse strain curve.

*Indicates Strain Measurement by Resistance Strain Gages.

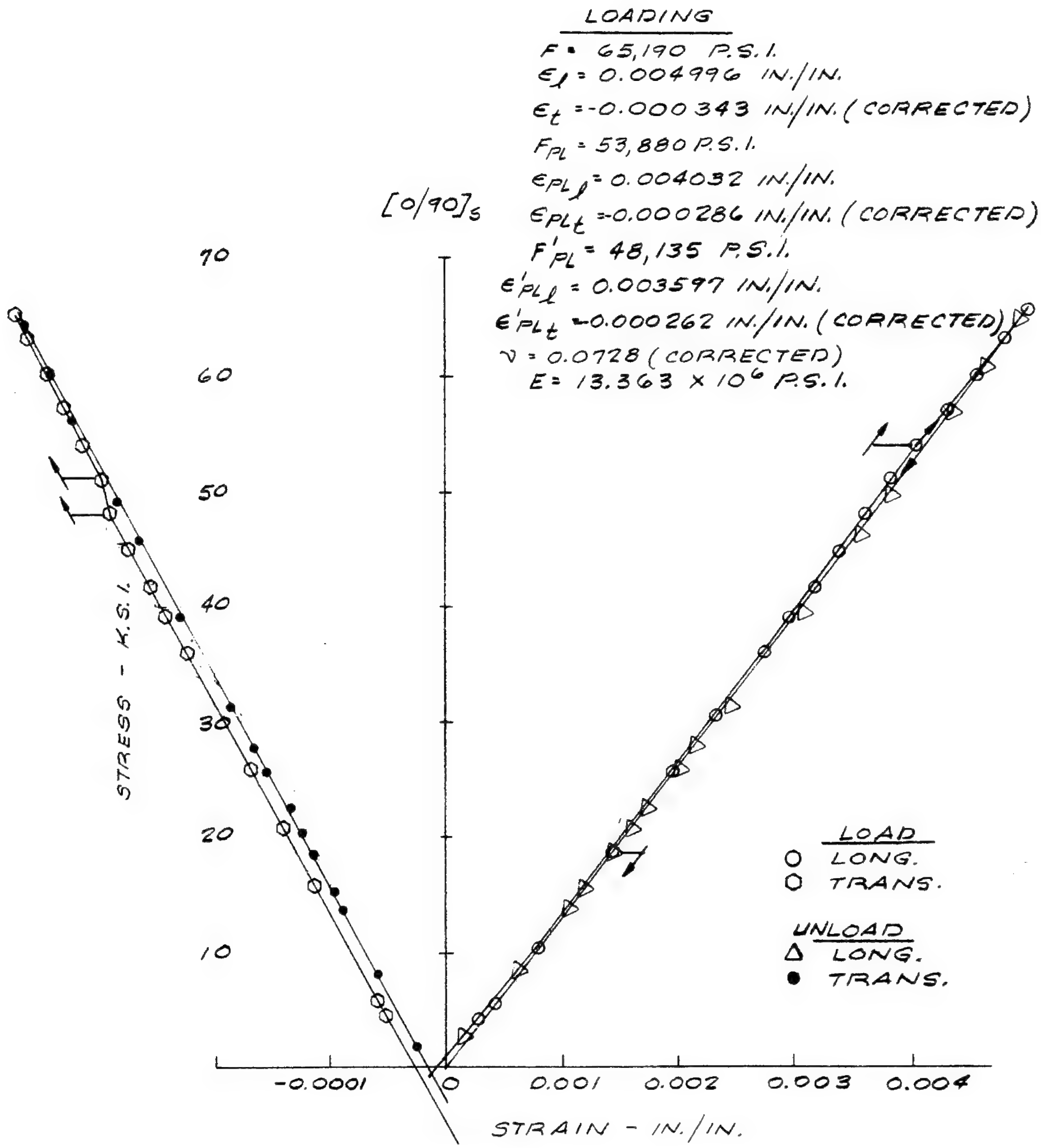


FIGURE II.30 INITIAL LOAD TENSION STRESS VS STRAIN AND SECTION, 63H

TABLE II. 19

INITIAL/SUBSEQUENT TENSION FOR PHOTOMICROGRAPHS, C-48

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS   Lam. Orient. $[90/0]_S$

Matrix - ERL 2256   No. of Plies 4

Load Orient. 0^o

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☒, Comp ☐, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: Std. Straight Sided, SwRI 03-401

Soak at Temp: - °F for - hr   Test Temp. RT °F

Property	Panel No.		C-48								
	Spec. Ident.		5-11K	5-11L						Ave	
Stress (ksi)	ν_I		0.017	0.024						0.0205	
	ν_S		0.022	0.024						0.0230	
	F 75% I&S			28.69						28.69	29.10
	F 77% I&S		29.50							29.50	
	F_{ult}										
Modulus $E, G \times 10^{-6}$	E or G I&S (Primary)		13.20	11.74						12.47	
	E' or G' (Secondary)										
Strain in./in.	Proportional Limit	ϵ_1									
		ϵ_2									
		ϵ_{45}									
	Ultimate	ϵ_1									
		ϵ_2									
		ϵ_{45}									
Specimen Width (in.)											
Specimen Thick. (in.)											

Strain Gage No. EA-03-250BF 350   Properties Based on

Extensometer TSMD Dual Range   Nominal ☐; Actual ☒

Filament Count - /in. Void Content 1.56 % Ply Thick. 0.00825 in.

Fil. Vol. Fract. 0. 5545 Resin Wt. Fract. 0.____ Lam. Density 0.0560 lb/in.³

Laminate: Tape or Matrix Design broadgoods-mil. Manuf. Fiberite

Balance Ply n/a Cure Spec SwRI S3-303

Organization :

Comments: Specimens 5-11K and 5-11L were stressed to values shown, then sectioned for microscopic examination. Q.C. tests were low as were ultimate tensile tests.

*Indicates Strain Measurement by Resistance Strain Gages.

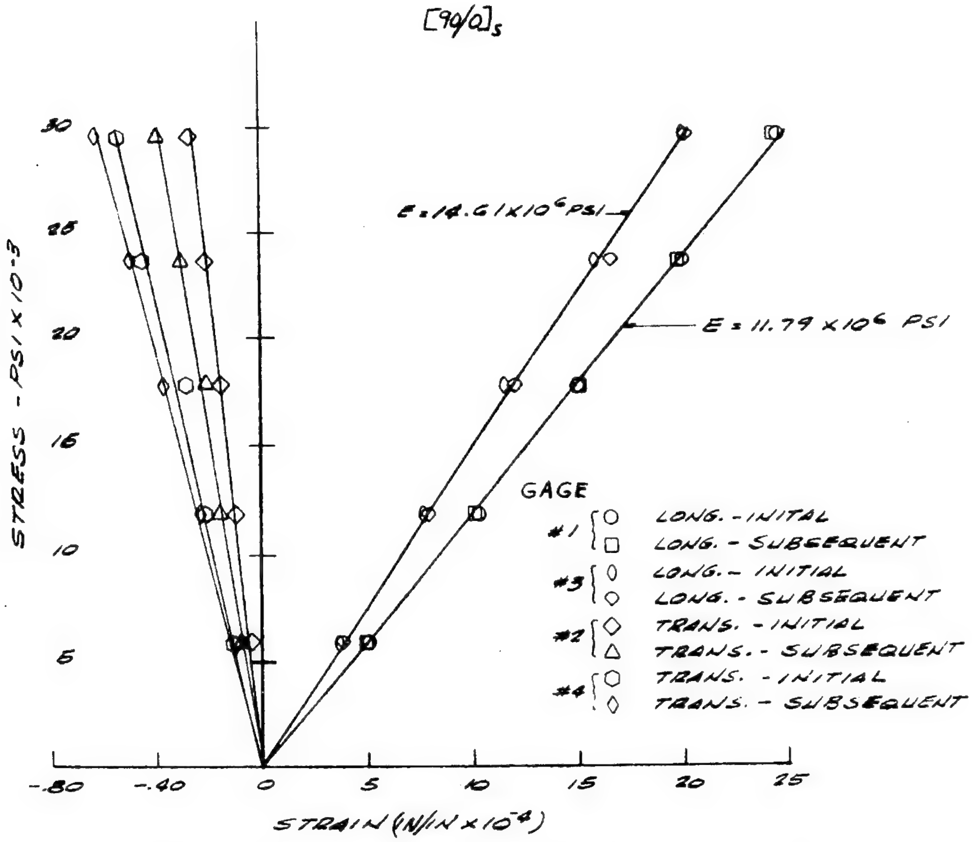


FIGURE II. 31. STRESS VS STRAIN, 5-11K
(STRAIN GAGES, BACK-TO-BACK)

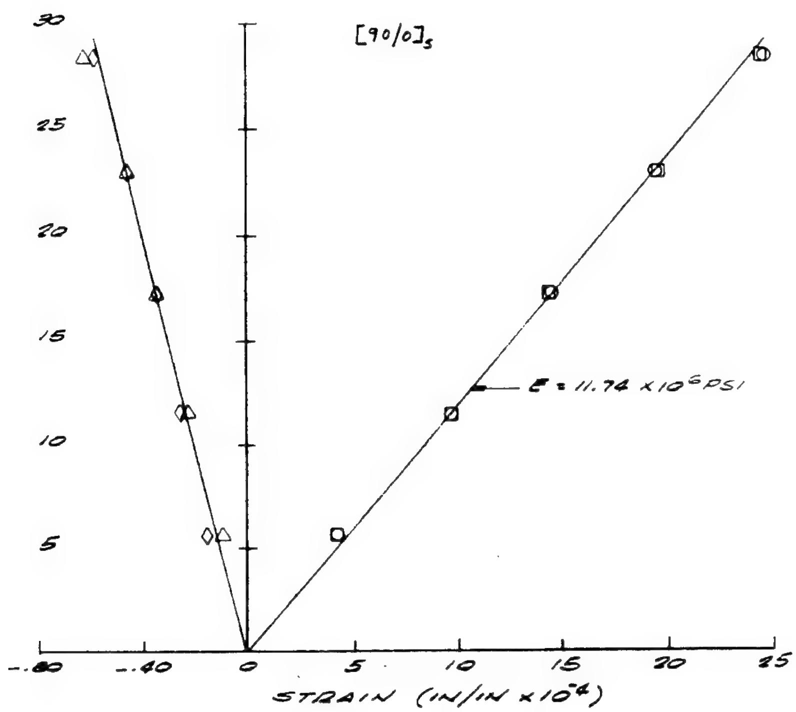


FIGURE II. 32. STRESS VS STRAIN,
5-11L (STRAIN GAGE)

APPENDIX II. 4

INITIAL/SUBSEQUENT COMPRESSION TESTS

TABLE II. 20

INITIAL COMPRESSION/SUBSEQUENT COMPRESSION, C-57

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS — Lam. Orient. $[0/90_2/0]_{3T}$

Matrix - ERL-2256 — No. of Plies 12

Load Orient. 0°

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☐, I/S Comp ☒, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: SwRI Standard Compression (UT/C)*

Soak at Temp: -- °F for -- hr Test Temp. RT °F

Property			Panel No. C-57								
		Spec. Ident.	57-E	57-N	57-W					Ave	S.D.
Stress (ksi)	F_{pl}										
	$F_{.70}$ (I)		56.61	57.04	55.95					56.54	
	F__										
	F__										
	F_{ult} (S)		78.98	87.40	70.62					79.00	
Modulus $E, G \times 10^{-6}$	E or G (I)		8.83	9.32	9.09					9.08	
	E' or G' (S)		9.65	9.52	8.97					9.38	
* Strain in./in.	Proportional Limit	ϵ_1									
		ϵ_2									
		ϵ_{45}									
	Ultimate	ϵ_1	0.00894	0.00908	0.00779						
		ϵ_2									
		ϵ_{45}									
Specimen Width (in.)			0.498	0.499	0.499					0.4987	
Specimen Thick. (in.)			0.105	0.104	0.106					0.105	

(70.4% F_{CU})

Strain Gage No. MM EP08-015DJ-120 — Properties Based on

Extensometer B. Compressometer PC7M(P)1012 — Nominal ☐; Actual ☒

Filament Count -- /in. Void Content 0.92 % Ply Thick. 0.0088 in.

Fil. Vol. Fract. 0.5661 Resin Wt. Fract. 0. -- Lam. Density 0.0551 lb/in.^{3}

Laminate: Tape or Matrix Design Broadgoods-M. L. Manuf. Fiberite

Balance Ply N/A Tow Cure Spec SwRI S-3-303

Organization: SwRI

Comments: *Reference SwRI Drawing 03-2776-01-3.

*Indicates Strain Measurement by Resistance Strain Gages.

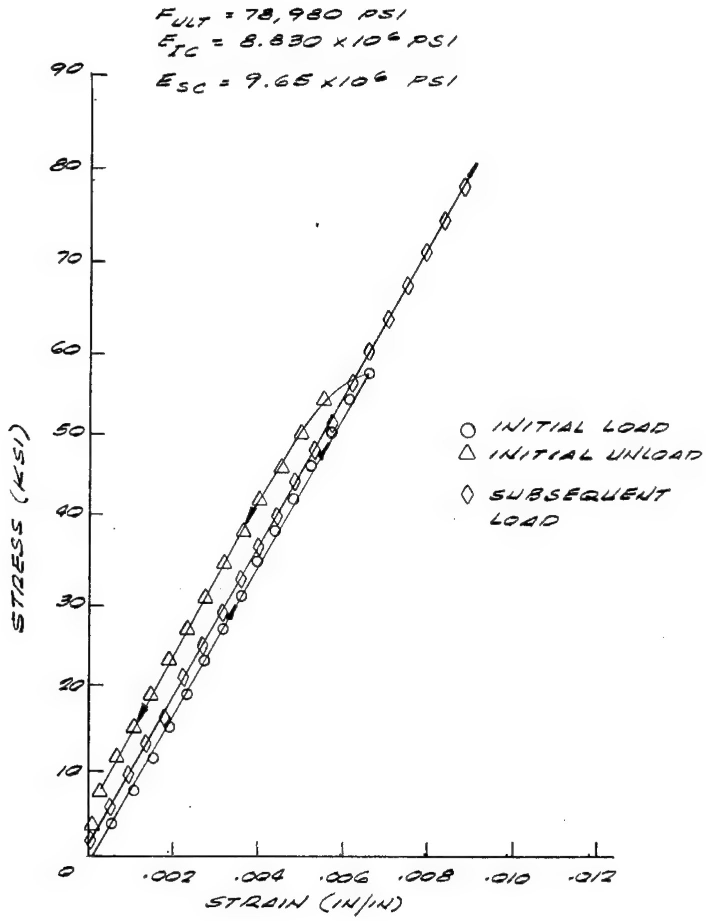


FIGURE II. 33. STRESS VS STRAIN, SPECIMEN 57-E
(Compression)

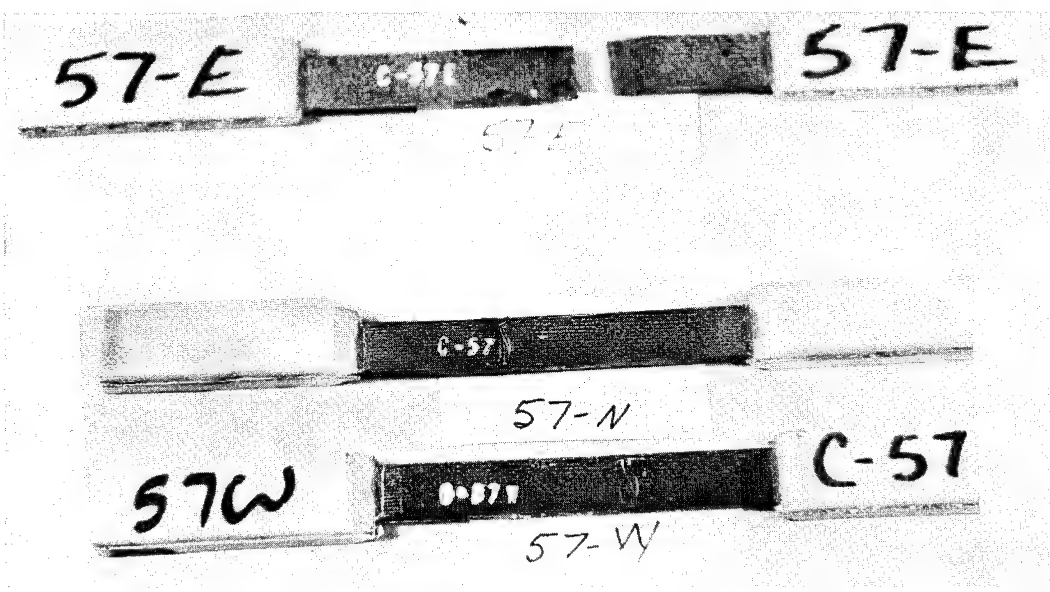


FIGURE II. 34. I/S COMPRESSION SPECIMENS 57-E, N, W AFTER FAILURE, $[0/90_2/0]_{3T}$

TABLE II. 21

INITIAL/SUBSEQUENT STATIC COMPRESSION, C-49

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS - Treated Lam. Orient. $[0]_{12T}$

Matrix - ERL 2256 No. of Plies 12

Load Orient. 0^o

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☐, Comp ☒, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: SwRI Standard Compression **

Soak at Temp: -- °F for -- hr Test Temp. RT °F

Property												
	Panel No.		C-49									
	Spec. Ident.		5-5A								Ave	
Stress (ksi)	F_{pl}											
	F__											
	F__											
	F Initial		101.2									(76.1 % F_{CU})
	F_{ult} Subs.		119.4									
Modulus $E, G \times 10^{-6}$	E or G (I) (Primary)		20.6									
	E' or G' (Secondary)											
*Strain in./in.	Proportional Limit	ϵ_1										
		ϵ_2										
		ϵ_{45}										
	Ultimate	ϵ_1	0.00059									
		ϵ_2										
		ϵ_{45}										
Specimen Width (in.)			0.499									
Specimen Thick. (in.)			0.099									

Strain Gage No. EP-08-015 DT-120 Properties Based on

Extensometer Model PC-7M Compressometer Nominal ☐; Actual ☒

Filament Count -- /in. Void Content 3.39 % Ply Thick. 0.0083 in.

Fil. Vol. Fract. 0.6187 Resin Wt. Fract. 0.____ Lam. Density .0564 lb/in.^{3}

Laminate: Tape or Matrix Design Broadgoods - M. L. Manuf. Fiberite

Balance Ply n/a Cure Spec SwRI S3-303

Organization : SwRI

Comments: Note: Specimen 5-5A was loaded to 5,000 lbs. unloaded, then loaded to failure; modulus values given are the average for both gages on each specimen.

*Indicates Strain Measurement by Resistance Strain Gages.

**Reference SwRI Drawing 03-2776-01-3.

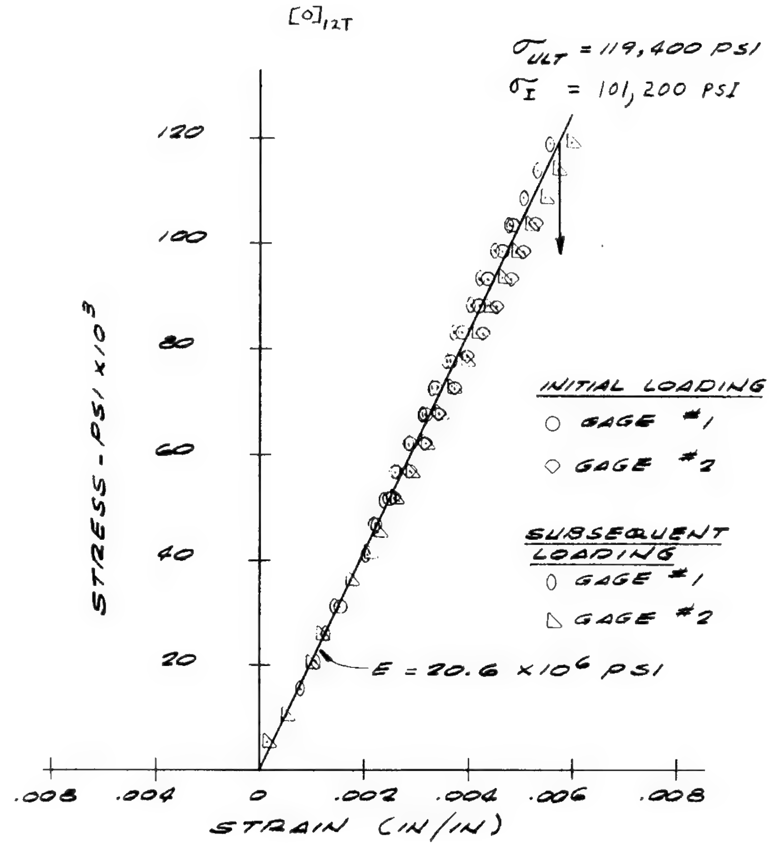


FIGURE II. 35. STRESS VS STRAIN,
SPECIMEN 5-5A (COMPRESSION)

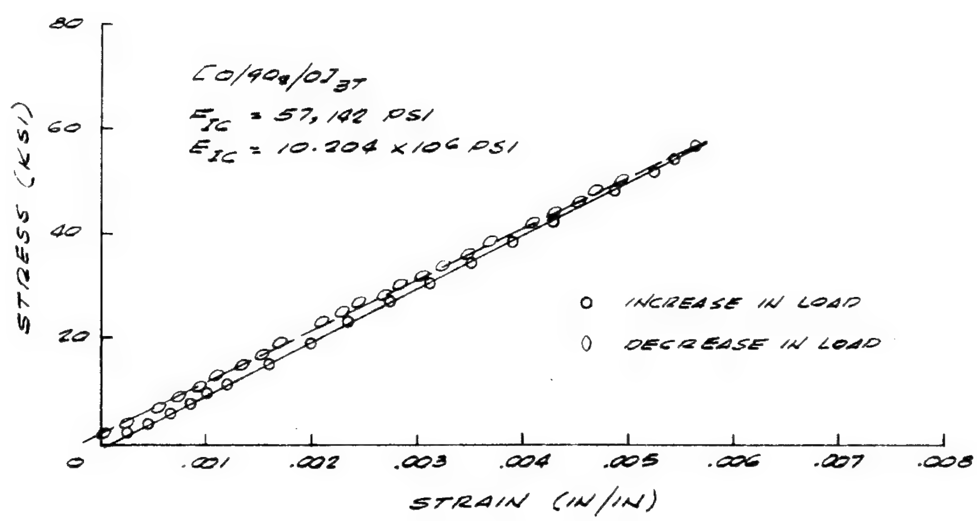


FIGURE II. 36. STRESS VS STRAIN,
SPECIMEN 57-P
(Initial Compression)

TABLE II. 22

INITIAL COMPRESSION/SUBSEQUENT SECTION, C-57

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtald's HTS — Lam. Orient. $[0/90_2/0]_{3T}$

Matrix - ERL-2256 — No. of Plies 12

Load Orient. 0^o

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☐, Initial Comp ☒, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐, Subsequent Section and Photomicrograph ☒

Type Test Specimen: SwRI UT/C Test Specimen*

Soak at Temp: -- °F for -- hr Test Temp. RT °F

Property		Panel No.	C-57								
		Spec. Ident.	57-D	57-P						Ave	
Stress (ksi)	F_{pl}										
	F Initial C.		55.343	57.142						56.242	(70.1% F_{CU})
	F —										
	F —										
	F_{ult}										
Modulus E, Gx10^{-6}	E or G (Primary)		9.073	10.204						9.638	
	E' or G' (Secondary)										
*Strain in./in.	Proportional Limit	ϵ_1									
		ϵ_2									
		ϵ_{45}									
	Ultimate	ϵ_1	0.00610	0.00572						0.00591	
		ϵ_2									
		ϵ_{45}									
Specimen Width (in.)			0.499	0.498						0.498	
Specimen Thick. (in.)			0.105	0.104						0.104	

Strain Gage No. MM EP08-015DJ-120 — Properties Based on

Extensometer B. Compression PC7M(P)-1012 — Nominal ☐; Actual ☒

Filament Count -- /in. Void Content 0.92 % Ply Thick. 0.0088 in.

Fil. Vol. Fract. 0.5661 Resin Wt. Fract. 0. -- Lam. Density 0.0551 lb/in.^{3}

Laminate: Tape or Matrix Design Broadgoods-M. L. Manuf. Fiberite

Balance Ply N/A Cure Spec SwRI S3-303

Organization: SwRI

Comments: *Reference SwRI Drawing 03-2776-01-3

*Indicates Strain Measurement by Resistance Strain Gages.

APPENDIX II. 5

INITIAL TENSION/SUBSEQUENT COMPRESSION TESTS

TABLE II. 23

INITIAL TENSION/SUBSEQUENT COMPRESSION, C-57

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS — Lam. Orient. $[0/90_2/0]_{3T}$

Matrix - ERL-2256 — No. of Plies 12

Load Orient. 0^o

Balance Ply Added: Yes ☐ No ☒

Loading Type: Initial Tension ☒, Subsequent Comp ☒, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: SwRI UT/C Specimen*

Soak at Temp: -- °F for -- hr Test Temp. RT °F

Property		Panel No.	C-57								
		Spec. Ident.	57-F	57-EE	57-M					Ave	S.D.
Stress (ksi)		F_{pl}								57EE, 57M	only
		F Initial -T.	64.8	52.227	54.410					53.318	
		F —									
		F —									
		F_{ult} Subs.-C	56.168	81.9	74.856					78.378	
Modulus $E, G \times 10^{-6}$		E_{IT}		11.403	10.992					11.198	
		E_{SC}	10.750	10.000	9.560					9.780	
*Strain in./in.	Initial Tension (IT)	ϵ_1		0.00458	0.00495					0.00476	
		ϵ_2									
		ϵ_{45}									
	Subs. Comp. Ultimate (SC)	ϵ_1	0.00522	0.00875	0.00783					0.00829	
		ϵ_2									
		ϵ_{45}									
Specimen Width (in.)			0.498	0.500	0.499					0.499	
Specimen Thick. (in.)			0.105	0.107	0.104					0.105	

Strain Gage No. T=EA-03-250-BF-350; C=EP08-015DJ-120 — Properties Based on

Extensometer MM B. Dualrange TSM-D-1047; B. Compr. PCTM (P)-1012 — Nominal ☐; Actual ☒

Filament Count -- /in. Void Content 0.92 % Ply Thick. 0.0088 in.

Fil. Vol. Fract. 0.5661 Resin Wt. Fract. 0. -- Lam. Density 0.0551 lb/in.^{3}

Laminate: Tape or Matrix Design Broadgoods-M. L. Tow Manuf. Fiberite

Balance Ply N/A Cure Spec SwRI 3-303

Organization: SwRI

Comments: *Reference SwRI Drawing 03-2776-01-3.

*Indicates Strain Measurement by Resistance Strain Gages.

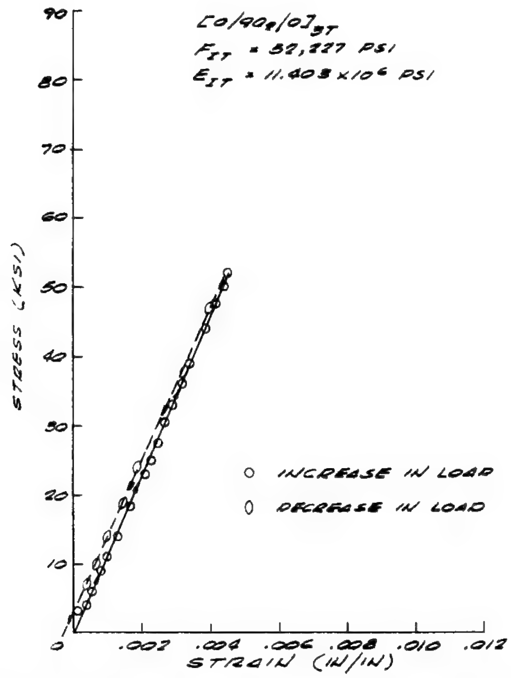


FIGURE II. 37. STRESS VS STRAIN, SPECIMEN 57-EE (<u>Initial Tension/</u> Subsequent Compression)

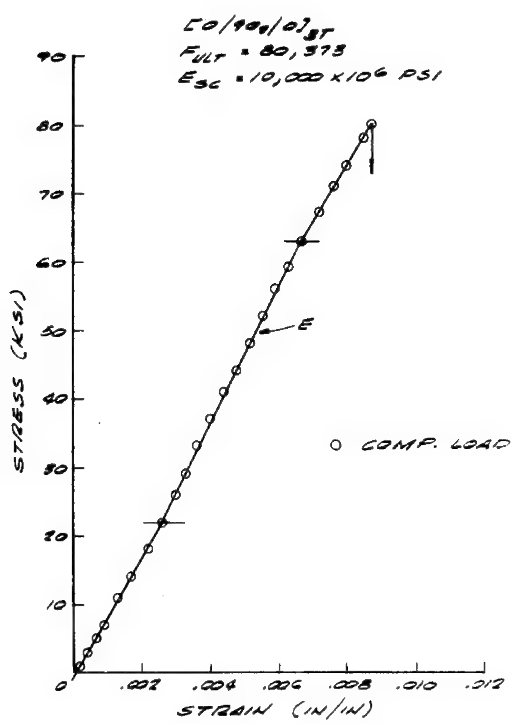


FIGURE II. 38. STRESS VS STRAIN, SPECIMEN 57-EE (Initial Tension/ <u>Subsequent Compression</u>)

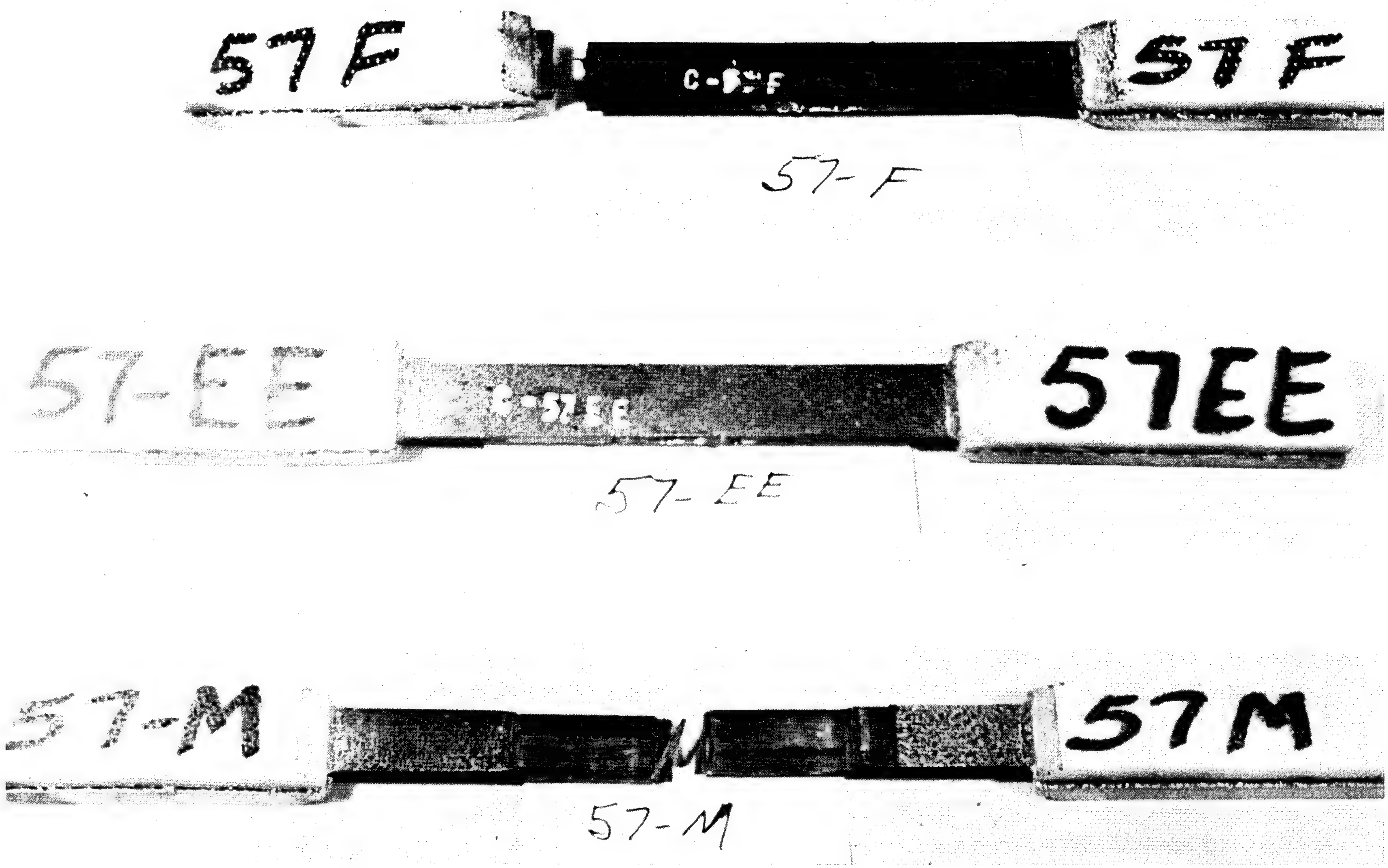


FIGURE II. 39. IT/SC SPECIMENS 57-F, EE, M AFTER FAILURE, $[0/90_2/0]_{3T}$

TABLE II.24

INITIAL TENSION/SUBSEQUENT COMPRESSION/SECTION, C-57

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS   Lam. Orient. $[0/90_2/0]_{3T}$

Matrix - ERL-2256   No. of Plies 12

Load Orient. 0^o

Balance Ply Added: Yes ☐ No ☒

Loading Type: Initial Tension ☒, Subseq. #1 Comp ☒, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐, Subsequent #2 Section and Photomicrograph ☒

Type Test Specimen: SwRI UT/C Test Specimens*

Soak at Temp: -- °F for -- hr   Test Temp. RT °F

Property		Panel No.	C-57								
		Spec. Ident.	57-GG	57-G						Ave	S. D.
Stress (ksi)	F_{pl}										
	F Initial - T		52.404	54.229						53.316	
	F Subseq.-C		63.414	57.528						60.471	
	F ___										
	F_{ult}										
Modulus $E, Gx10^{-6}$	E_{IT} (Primary)		10.587	9.514						10.050	
	ESC		9.395	8.046						8.720	
*Strain in./in.	Initial Ten. (IT)	ϵ_1	0.00495	0.00570						0.00532	
		ϵ_2									
		ϵ_{45}									
	Subs. Comp. (SC)	ϵ_1	0.00675	0.00715						0.00695	
		ϵ_2									
		ϵ_{45}									
Specimen Width (in.)			0.498	0.498						0.498	
Specimen Thick. (in.)			0.107	0.104						0.106	

Strain Gage No. MM T=EA03-250BF-350; C=EP08-015PJ-120   Properties Based on

Extensometer B. Dualrange TSM D-1047; B. Compr. PC7M   Nominal ☐; Actual ☒

Filament Count -- /in. Void Content 0.92 % (P)-1012 Ply Thick. 0.0088 in.

Fil. Vol. Fract. 0.5661 Resin Wt. Fract. 0. -- Lam. Density 0.0551 lb/in.³

Laminate: Tape or Matrix Design Broadgoods-M. L. Manuf. Fiberite

Balance Ply N/A Tow Cure Spec SwRI S3-303

Organization: SwRI

Comments: *Reference SwRI Drawing 03-2776-01-3.

*Indicates Strain Measurement by Resistance Strain Gages.

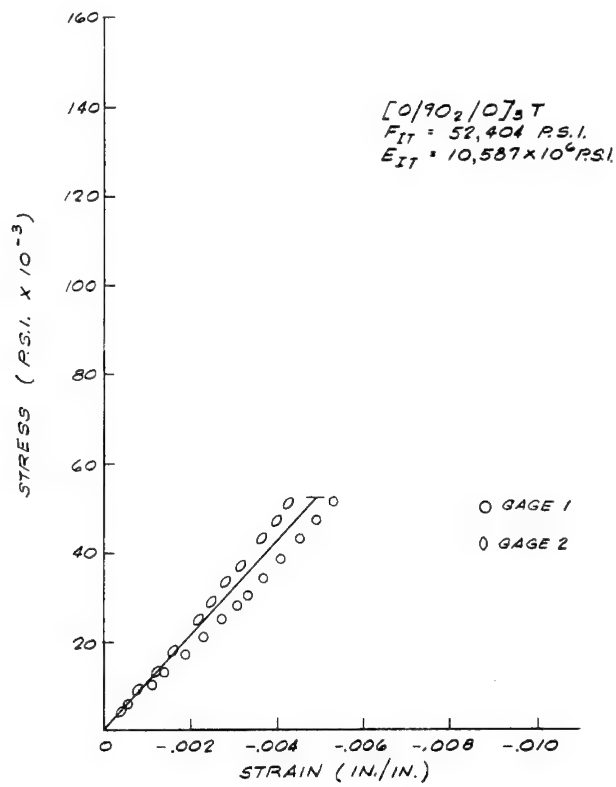


FIGURE II. 40. STRESS VS STRAIN, SPECIMEN 57-GG (Initial Tension/ Subsequent Compression)

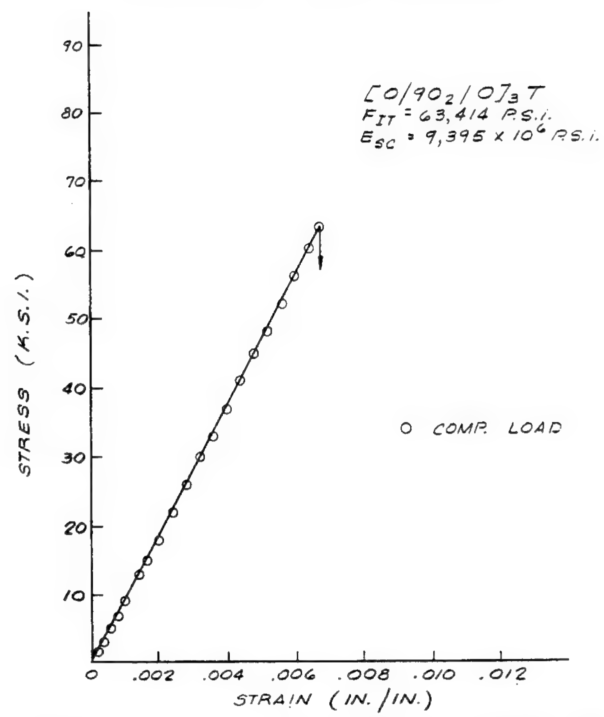


FIGURE II. 41. STRESS VS STRAIN, SPECIMEN 57-GG (Initial Tension/ Subsequent Compression)

APPENDIX II. 6

INITIAL COMPRESSION/SUBSEQUENT TENSION TESTS

TABLE II. 25

INITIAL COMPRESSION/SUBSEQUENT TENSION, C-57

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS   Lam. Orient. $[0/90_2/0]_{3T}$

Matrix - ERLA 2256   No. of Plies 12

Load Orient. 0^o

Balance Ply Added: Yes ☐ No ☒

Loading Type: Subsequent Tension ☒, Initial Comp ☒, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: SwRI UT/C Test Specimen*

Soak at Temp: -- °F for -- hr   Test Temp. RT °F

Property		Panel No.	C-57								
		Spec. Ident.	57-A	57-AA	57-FF					Ave	S.D.
Stress (ksi)	F_{pl}										
	F Initial-C		56.436	56.285	56.074					56.265	
	F__										
	F__										
	F_{ult} Subs.-T		67.946	64.564	67.780					66.763	
Modulus $E, G \times 10^{-6}$	E_{IC} (Primary)		8.690	8.864	8.528					8.694	
	E_{ST} (Secondary)		9.706	11.039	10.348					10.364	
*Strain in./in.	Initial Comp. (IC)	ϵ_1	0.00710	0.00635	0.00665					0.00670	
		ϵ_2								0.00621	
		ϵ_{45}									
	Subs. Ten. Ultimate (S.T.)	ϵ_1	0.00700	0.00615	0.00550						
		ϵ_2									
		ϵ_{45}									
Specimen Width (in.)			0.501	0.498	0.500					0.500	
Specimen Thick. (in.)			0.107	0.107	0.107					0.107	

Strain Gage No. T = EA-03-250-BF-350; C=EP08-0150J-120 MM   Properties Based on

Extensometer Baldwin Dualrange TSM-D-1047, B. Compressometer PC7M(P) 1012   Nominal ☐; Actual ☒

Filament Count -- /in.   Void Content 0.92 %   Ply Thick. 0.0088 in.

Fil. Vol. Fract. 0.5661   Resin Wt. Fract. 0. --   Lam. Density 0.0551 lb/in.^{3}

Laminate: Tape or Matrix Design Broadgoods-M. L. Tow   Manuf. Fiberite

Balance Ply N/A   Cure Spec SwRI 3-303

Organization: SwRI

Comments: *Reference SwRI Drawing 03-2776-01-3.

*Indicates Strain Measurement by Resistance Strain Gages.

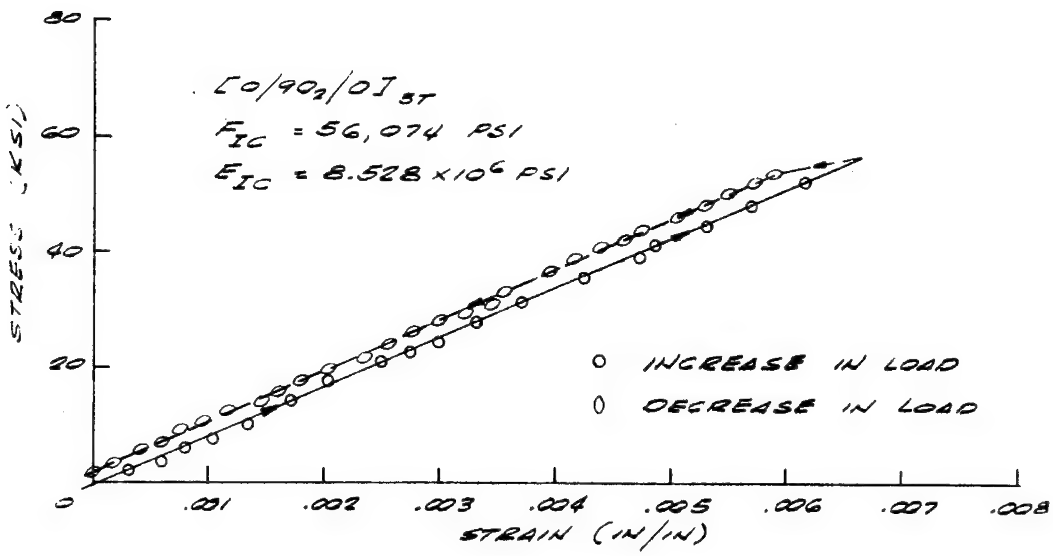


FIGURE II. 42. STRESS VS STRAIN, SPECIMEN 57-FF
(Initial Compression/Subsequent Tension)

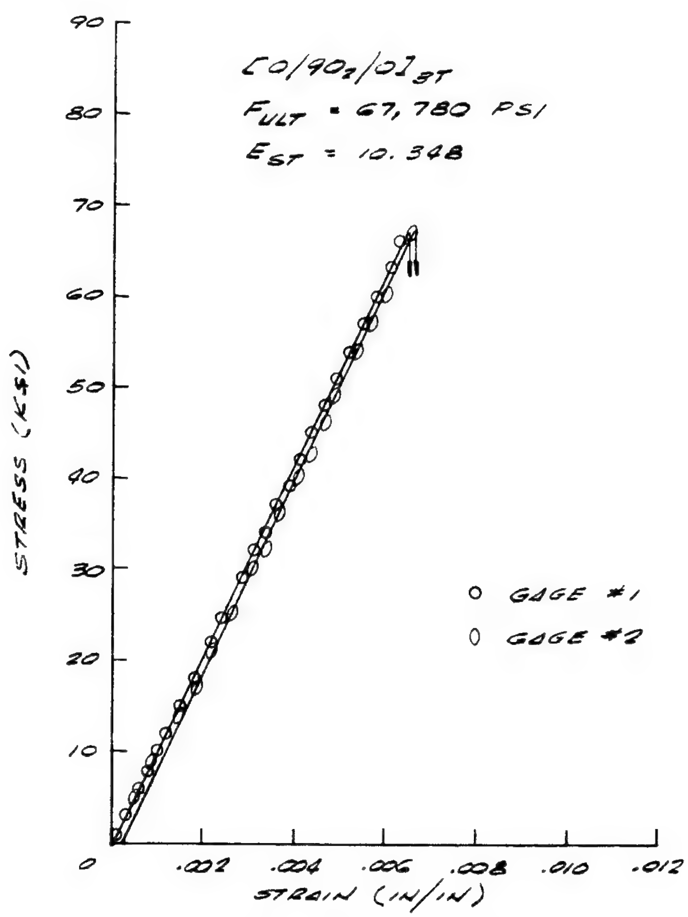


FIGURE II. 43. STRESS VS STRAIN,
SPECIMEN 57-FF
(Initial Compression/Subsequent Tension)

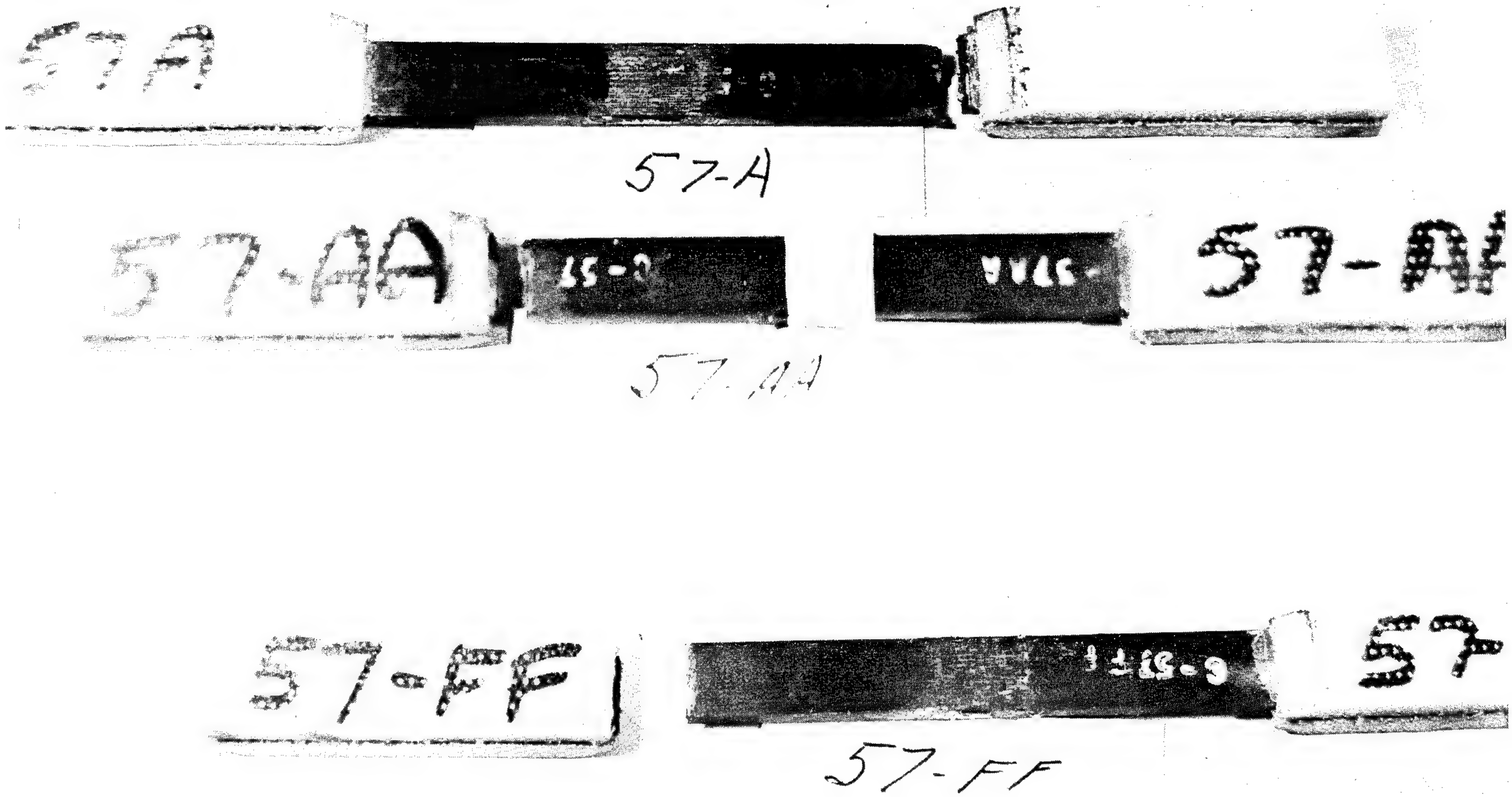


FIGURE II. 44. IC/ST SPECIMENS 57-A, AA, FF AFTER FAILURE, $[0/90_2/0]_{3T}$

TABLE II. 26

INITIAL COMPRESSION/SUBSEQUENT TENSION/SECTION, C-57

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS   Lam. Orient. $[0/90_2/0]_{3T}$

Matrix - ERL-2256   No. of Plies 12

Load Orient. 0^o

Balance Ply Added: Yes ☐ No ☒

Loading Type: Subsequent #1 Tension ☒, Initial Comp ☒, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐, Subsequent #2 Section and Photomicrograph ☒

Type Test Specimen: SwRI UT/C Test Specimen*

Soak at Temp: -- °F for -- hr   Test Temp. RT °F

Property		Panel No.	C-57								
		Spec. Ident.	57-K	57-CC						Ave	S. D.
Stress (ksi)		F_{pl}									
		F Initial-C.	55.662	56.226						55.944	
		F Subseq.-T	65.992	61.654						63.823	
		F —		↓							
		F_{ult} Fail.-T		61.654							
Modulus E,Gx10^{-6}		E IC (Primary)	9.185	9.444						9.314	
		EST	11.329	11.514						11.422	
*Strain in./in.	Initial Comp. (IC)	ϵ_1	0.00606	0.00573						0.00590	
		ϵ_2									
		ϵ_{45}									
	Subs. Ten. (ST)	ϵ_1	0.00582	0.00530						0.00556	
		ϵ_2									
		ϵ_{45}									
Specimen Width (in.)			0.501	0.508						0.504	
Specimen Thick. (in.)			0.104	0.106						0.105	

Strain Gage No. MM T=EA-03-240-BF-350; C=EP08-015DJ-120   Properties Based on

Extensometer B. Dualrange TSM D-1047; B. Compr. PC7M   Nominal ☐; Actual ☒

Filament Count (P)-1012 -- /in. Void Content 0.92 % Ply Thick. 0.0088 in.

Fil. Vol. Fract. 0.5661 Resin Wt. Fract. 0. -- Lam. Density 0.0551 lb/in.^{3}

Laminate: Tape or Matrix Design Broadgoods-M. L. Manuf. Fiberite

Balance Ply N/A Tow Cure Spec SwRI S3-303

Organization: SwRI

Comments: *Reference SwRI Drawing 03-2776-01-3

*Indicates Strain Measurement by Resistance Strain Gages.

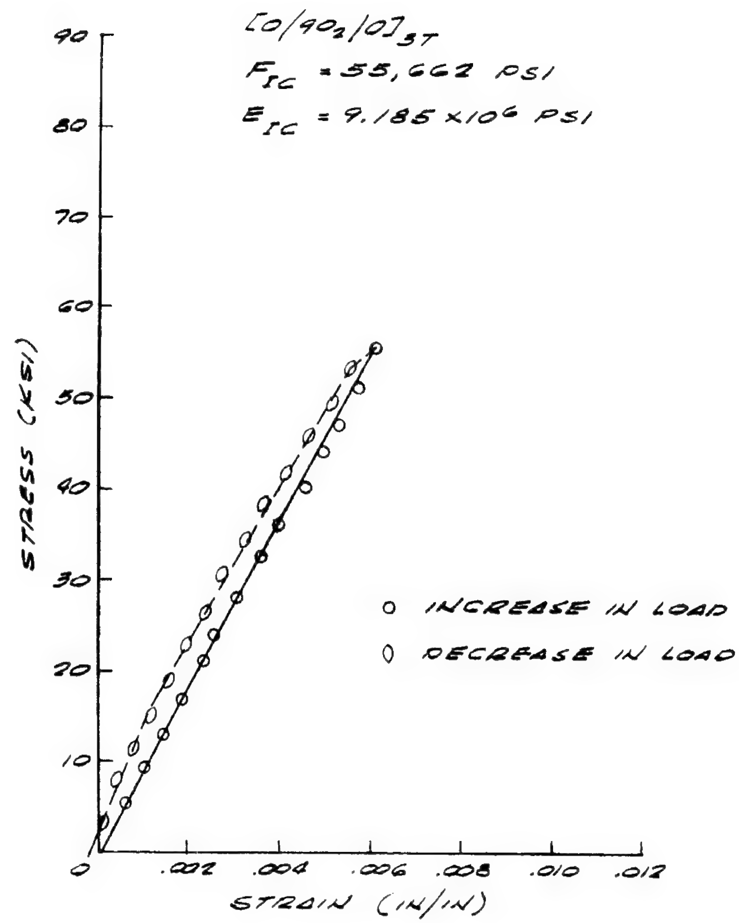


FIGURE II. 45. STRESS VS STRAIN, SPECIMEN 57-K
(Initial Compression/Subsequent Tension)

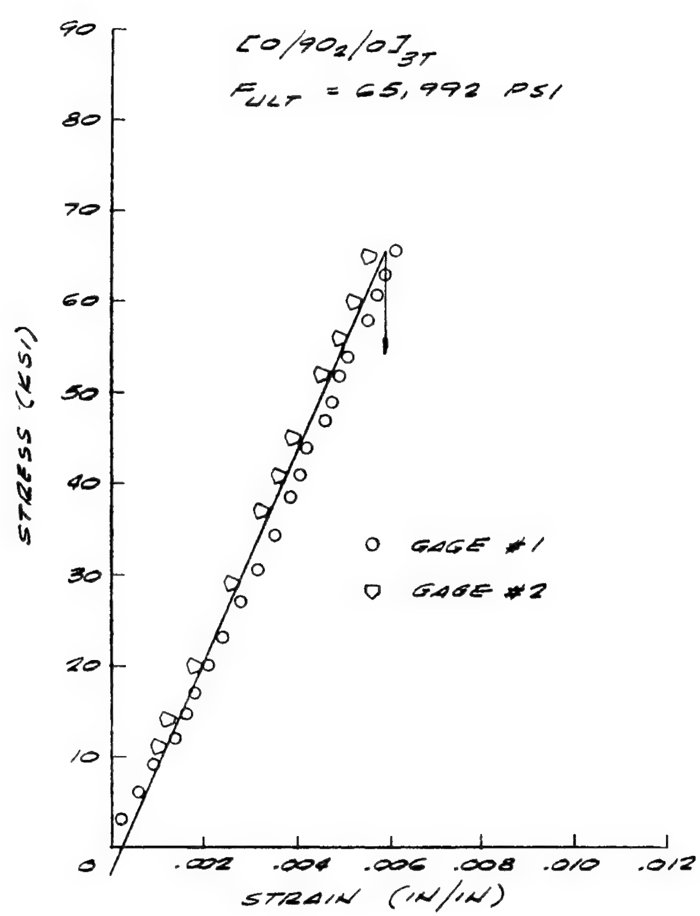


FIGURE II. 46. STRESS VS STRAIN, SPECIMEN 57-K
(Initial Compression/Subsequent Tension)

APPENDIX II. 7

INCREMENTAL TENSION LOAD TESTS

TABLE II.27 (page 1 of 2)

STATIC INCREMENTAL LOADING TENSION, C-39 (5-11D)

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS - Treated Lam. Orient. $[90/0]_S$

Matrix - ERL 2256 No. of Plies 4

Load Orient. 0^{o}

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☒, Comp ☐, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: Standard Straight Sided, SwRI 03-401

Soak at Temp: n/a °F for - hr Test Temp. RT °F

Property		Panel No.	C-39, Specimen 5-11D								
		Ld Cycle	250	500	750	1000	1250	1500	1750	Ave	S.D.
Stress (ksi)	F_{pl}										
	F__										
	F__										
	F__										
	F_{ult}										
Modulus $E, G \times 10^{-6}$	E (extens.)		15.07	15.07	15.76	11.55	12.38	12.38	11.55		
	E (strain gage)										
Strain in./in.	Proportional Limit	ϵ_1									
		ϵ_2									
		ϵ_{45}									
	Ultimate	ϵ_1									
		ϵ_2									
		ϵ_{45}									
Specimen Width (in.)										0.995	
Specimen Thick. (in.)										0.029	

Strain Gage No.

Extensometer TSMD Dual Range

Properties Based on Nominal ☐; Actual ☒

Filament Count -- /in. Void Content 3.34 % Ply Thick. .00725 in.

Fil. Vol. Fract. 0.597 Resin Wt. Fract. 0.____ Lam. Density .0559 lb/in.^{3}

Laminate: Tape or Matrix Design broadgoods-M. L. Manuf. Fiberite

Balance Ply N/A Cure Spec SwRI S3-303

Organization: SwRI

Comments:

*Indicates Strain Measurement by Resistance Strain Gages.

TABLE II.27 (page 2 of 2)

STATIC INCREMENTAL LOADING TENSION, C-39 (5-11D)

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS - Treated Lam. Orient. $[90/0]_S$

Matrix - ERL 2256 No. of Plies 4

Load Orient. 0

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☒, Comp ☐, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: Standard Straight Sided, SwRI 03-401

Soak at Temp: n/a °F for - hr Test Temp. RT °F

Property		Panel No.	C-39, Specimen 5-11D (Cont'd.)							Ave	S. D.
		Ld Cycle	2000	2250	Fail.						
Stress (ksi)	F_{pl}										
	F__										
	F__										
	F__										
	F_{ult}									81.80	
Modulus $E, G\times10^{-6}$	E (extens.)		13.33	14.44	12.84					13.437	
	E (strain gage)										
Strain in./in.	Proportional Limit	ϵ_1									
		ϵ_2									
		ϵ_{45}									
	Ultimate	ϵ_1									
		ϵ_2									
		ϵ_{45}									
Specimen Width (in.)											
Specimen Thick. (in.)											

Strain Gage No.

Extensometer TSMD Dual Range

Properties Based on Nominal ☐; Actual ☒

Filament Count -- /in. Void Content 3.34 % Ply Thick. 0.00725 in.

Fil. Vol. Fract. 0.597 Resin Wt. Fract. 0.___ Lam. Density 0.0559 lb/in.³

Laminate: Tape or Matrix Design broadgoods-M. L. Manuf. Fiberite

Balance Ply N/A Cure Spec SwRI S3-303

Organization: SwRI

Comments:

*Indicates Strain Measurement by Resistance Strain Gages.

TABLE II.28 (page 1 of 2)

CYCLIC LOAD STATIC TENSION, C-63 (63B)

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS - Treated   Lam. Orient. $[0/90]_S$

Matrix - ERL 2256   No. of Plies 4

Load Orient. 0^o

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☒, Comp ☐, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: Standard Straight Sided, SwRI 03-401

Soak at Temp: - °F for - hr   Test Temp. RT °F

Property		Panel No.	C-63, Specimen 63-B								
		Spec. Ident.	250	500	750	1000	1250	1500	1750	Ave	S.D.
Stress (ksi)	F_{pl}										
	F__										
	F__										
	F__										
	F_{ult}										
Modulus $E, G \times 10^{-6}$	E or G strain gage		11.56	12.00	12.13	12.16	12.19	12.13	12.11		
	E' or G' extensom.										
Strain in./in.	Proportional Limit	ϵ_1									
		ϵ_2									
		ϵ_{45}									
	Ultimate	ϵ_1									
		ϵ_2									
		ϵ_{45}									
Specimen Width (in.)			0.751								
Specimen Thick. (in.)			0.036								

Strain Gage No. EA-03-250 BF-350   Properties Based on

Extensometer TSMD Dual Range   Nominal ☐; Actual ☒

Filament Count -- /in. Void Content .02 % Ply Thick. .00900 in.

Fil. Vol. Fract. 0.5877 Resin Wt. Fract. 0.____ Lam. Density .0560 lb/in.^{3}

Laminate: Tape or Matrix Design broadgoods-M. L. Manuf. Fiberite

Balance Ply N/A Cure Spec SwRI S3-303

Organization: SwRI

Comments: Incremental loading to failure: 0-250-0; 0-500-0; 0-750-0, etc.

*Indicates Strain Measurement by Resistance Strain Gages.

TABLE II.28 (page 2 of 2)

CYCLIC LOAD STATIC TENSION, C-63 (63B)

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS - Treated Lam. Orient. $[0/90]_S$

Matrix - ERL 2256 No. of Plies 4

Load Orient. 0^o

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☒, Comp ☐, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: Standard Straight Sided, SwRI 03-401

Soak at Temp: - °F for - hr Test Temp. RT °F

Property		Panel No.	C-63, Specinen 63-B								
Property		Spec. Ident.	2000	2250	Fail.					Ave	S. D.
Stress (ksi)	(1) F'_{pl}				40.0					40.0	
	$F\_$										
	$F\_$			70.225							
	ν				0.040					0.040	
	F_{ult}				77.87					77.87	
Modulus $E, G \times 10^{-6}$	E or G strain gage		12.23	12.30	12.09					12.09	
	E' or G' extensom.										
Strain in./in.	Proportional Limit	ϵ_1									
		ϵ_2									
		ϵ_{45}									
	Ultimate	ϵ_1		0.00644	0.00644					0.00644	
		ϵ_2		0.00030	0.00030					0.00030	
		ϵ_{45}									
Specimen Width (in.)											
Specimen Thick. (in.)											

Strain Gage No. EA 03-250 BF-350 Properties Based on

Extensometer Nominal ☐; Actual ☒

Filament Count -- /in. Void Content .02 % Ply Thick. 0.00900 in.

Fil. Vol. Fract. 0.5877 Resin Wt. Fract. 0. Lam. Density .0560 lb/in.^{3}

Laminate: Tape or Matrix Design Broadgoods, M. L. Manuf. Fiberite

Balance Ply N/A Cure Spec SwRI S3-303

Organization: SwRI

Comments: (1) Longitudinal stress at which transverse strain knee occurred.

*Indicates Strain Measurement by Resistance Strain Gages.

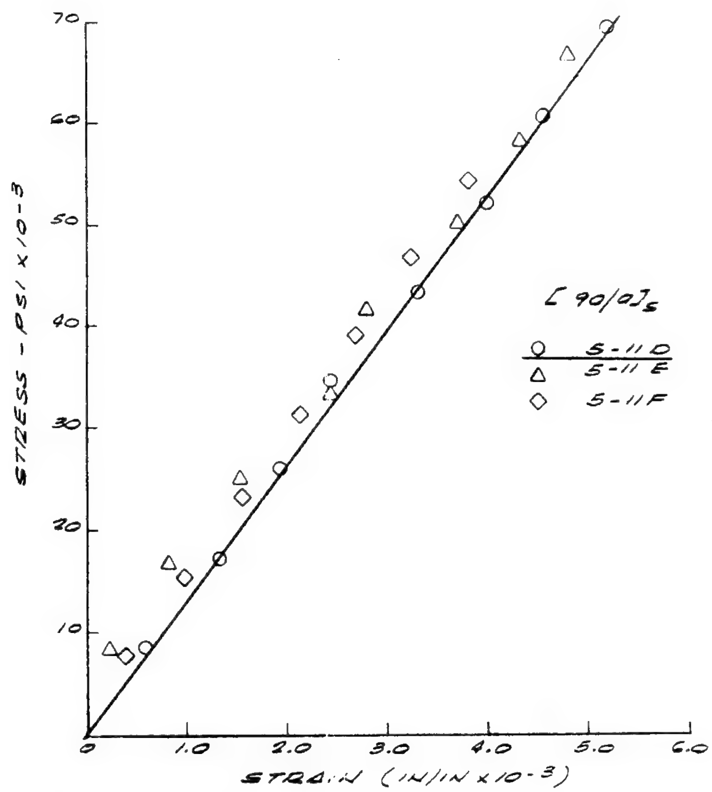


FIGURE II. 47. STRESS/STRAIN CURVE FROM INCREMENTAL LOADING TESTS, C-39

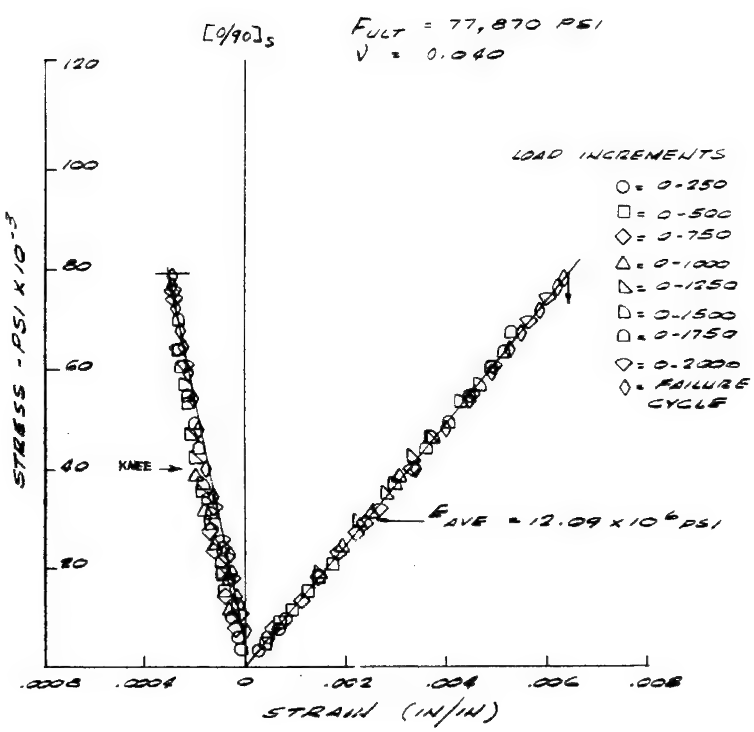


FIGURE II. 48. STRESS VS STRAIN, 63-B

TABLE II. 29 (page 1 of 2)

INCREMENTAL LOADING, C-63 (63M)

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS — Lam. Orient. $[0/90]_S$

Matrix - ERL-2256 — No. of Plies 4

Load Orient. 0^{o}

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☒, Comp ☐, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: Std Straight Sided, SwRI 03-401

Soak at Temp: - °F for - hr Test Temp. RT °F

Property		Panel No.	C-63, Specimen 63M								
		Load cycle	250	500	750	1000	1250	1500	1750	Ave	S. D.
Stress (ksi)		F_{pl}									
		F__									
		F__									
		F__									
		F_{ult}									
* Modulus $E, G x 10^{-6}$		E or G (Primary)		11.86	12.38	12.48	12.64	12.83	12.81		
		E' or G' (Secondary)									
Strain in./in.	Proportional Limit	ϵ_1									
		ϵ_2									
		ϵ_{45}									
	Ultimate	ϵ_1									
		ϵ_2									
		ϵ_{45}									
Specimen Width (in.)			0.750								
Specimen Thick. (in.)			0.036								

Strain Gage No. EA-03-250BF-350

Extensometer TSMD Dual Range

Properties Based on Nominal ☐; Actual ☒

Filament Count - /in. Void Content 0.02 % Ply Thick. 0.0090 in.

Fil. Vol. Fract. 0.5877 Resin Wt. Fract. 0.___ Lam. Density 0.0560 lb/in.^{3}

Laminate: Tape or Matrix Design broadgoods - M. L. tow Manuf. Fiberite

Balance Ply n/a Cure Spec SwRI S3-303

Organization: SwRI

Comments:

*Indicates Strain Measurement by Resistance Strain Gages.

TABLE II. 29 (page 2 of 2)

INCREMENTAL LOADING, C-63 (63M)

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS Lam. Orient. [0/90]S

Matrix - ERL-2256 No. of Plies 4

Load Orient. 0°

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☒, Comp ☐, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: Std Straight Sided, SwRI 03-401

Soak at Temp: - °F for - hr Test Temp. RT °F

Property		Panel No.	C-63, Specimen 63M								
		Spec. Ident.	1840	1840F						Ave	S.D.
Stress (ksi)	F_{pl}										
	F__										
	F__										
	F__										
	F_{ult}			67.972						67.972	
Modulus $E, G \times 10^{-6}$	E or G (Primary)		12.83	12.547						12.547	
	E' or G' (Secondary)										
Strain in./in.	Proportional Limit	ϵ_1									
		ϵ_2									
		ϵ_{45}									
	Ultimate	ϵ_1									
		ϵ_2									
		ϵ_{45}									
Specimen Width (in.)			0.750								
Specimen Thick. (in.)			0.036								

Strain Gage No. EA-03-250BF-350

Extensometer TSMD Dual Range

Properties Based on Nominal ☐; Actual ☒

Filament Count - /in. Void Content 0.02 % Ply Thick. 0.0090 in.

Fil. Vol. Fract. 0.5877 Resin Wt. Fract. 0.____ Lam. Density 0.0560 lb/in.^{3}

Laminate: Tape or Matrix Design broadgoods - M. L. tow Manuf. Fiberite

Balance Ply n/a Cure Spec SwRI S3-303

Organization : SwRI

Comments:

*Indicates Strain Measurement by Resistance Strain Gages.

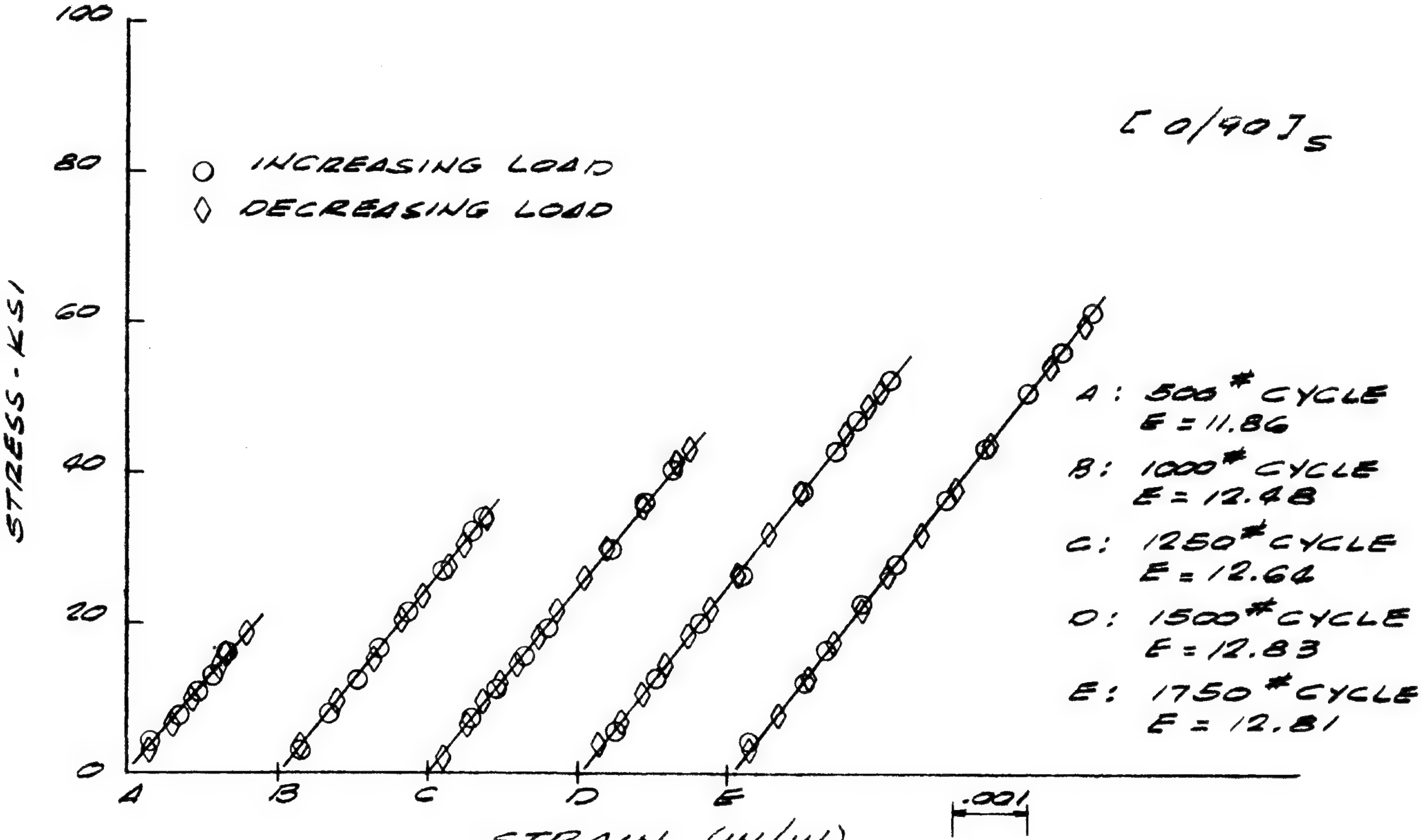


FIGURE II. 49 STRESS VS STRAIN, 63-M
(INCREMENTAL LOADING - TENSION)

APPENDIX II. 8

COMPRESSION INCREMENTAL LOAD TESTS

TABLE II.30

COMPRESSION INCREMENTAL LOADING, C-40

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS - Treated   Lam. Orient. $[0/90_2/0]_{3T}$

Matrix - ERL 2256   No. of Plies 12

Load Orient. 0^{o}

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☐, Comp ☒, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: SwRI Standard Compression**

Soak at Temp: - °F for - hr Test Temp. RT °F

Property		Panel No.	C-40, Specimen 5-13B								
		Spec. Ident.	1000	1500	2000	2500	3000	3500	Fail	Ave	S.D.
Stress (ksi)		F_{pl}									
		F__									
		F__									
		F__									
		F_{ult}							78.09		
* Modulus $E, G \times 10^{-6}$		E or G (Primary)	10.25	10.17	9.86	10.11	10.08	10.12	10.04	10.09	
		E' or G' (Secondary)						8.01	9.38		
* Strain in./in.	Proportional Limit	ϵ_1									
		ϵ_2									
		ϵ_{45}									
	Ultimate	ϵ_1							0.00768		
		ϵ_2									
		ϵ_{45}									
Specimen Width (in.)									0.504		
Specimen Thick. (in.)									0.101		

Strain Gage No. EP 08-015 DJ-120   Properties Based on

Extensometer Model PC-7M Compressometer   Nominal ☐; Actual ☒

Filament Count - /in. Void Content 3.04 % Ply Thick. .00841 in.

Fil. Vol. Fract. 0.5571 Resin Wt. Fract. 0.____ Lam. Density .0552 lb/in.^{3}

Laminate: Tape or Matrix Design broadgoods-meter length Manuf. Fiberite

Balance Ply n/a Cure Spec SwRI S3-303

Organization : SwRI

Comments: Specimen loaded and unloaded in 250# increments until failure. 250 lbs is 4,912 psi.
(1)Ref. SwRI Dwg. 03-2776-01-3

*Indicates Strain Measurement by Resistance Strain Gages.

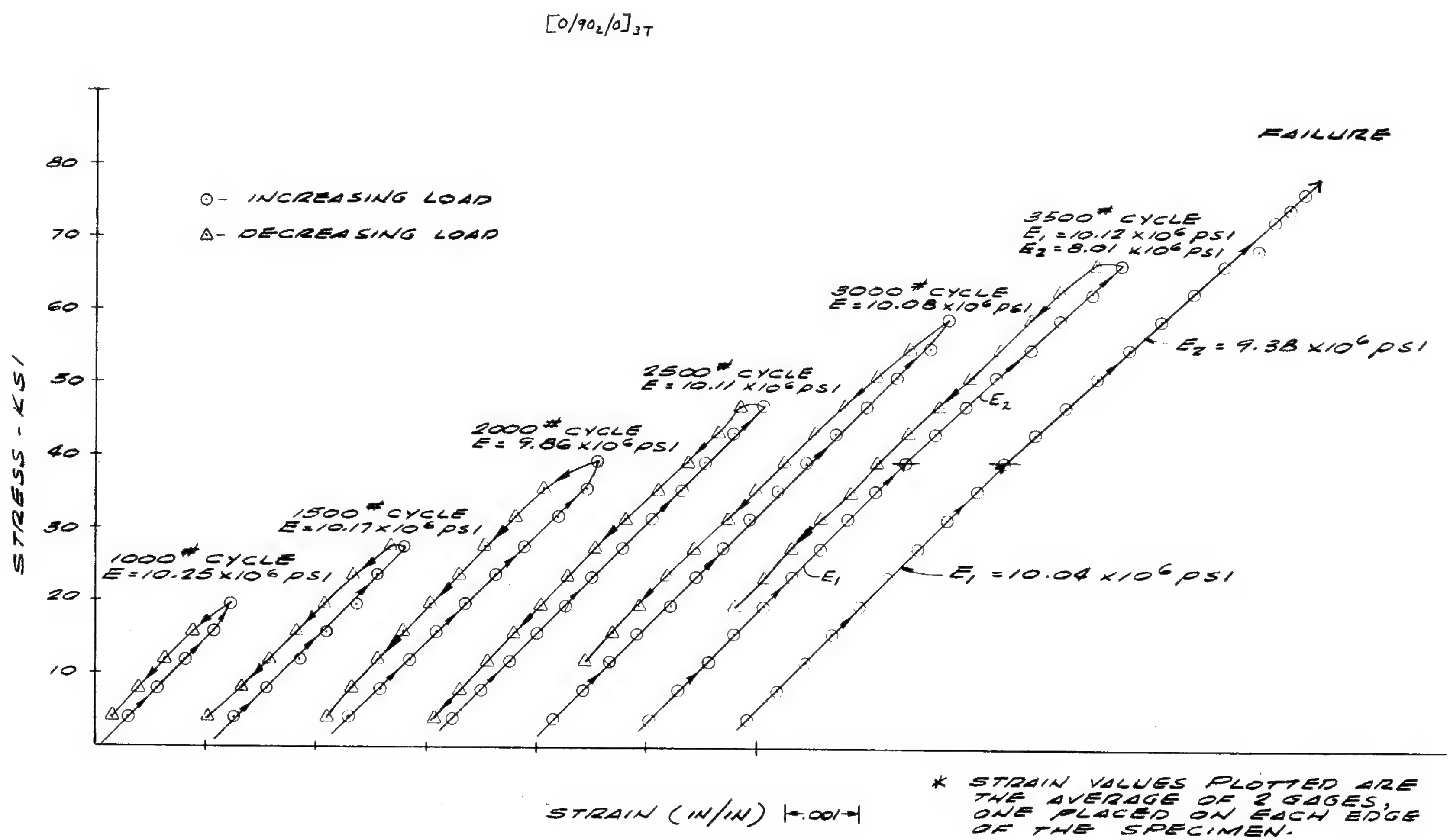


FIGURE II.50. STRESS VS STRAIN*, SPECIMEN 5-13B (COMPRESSION)

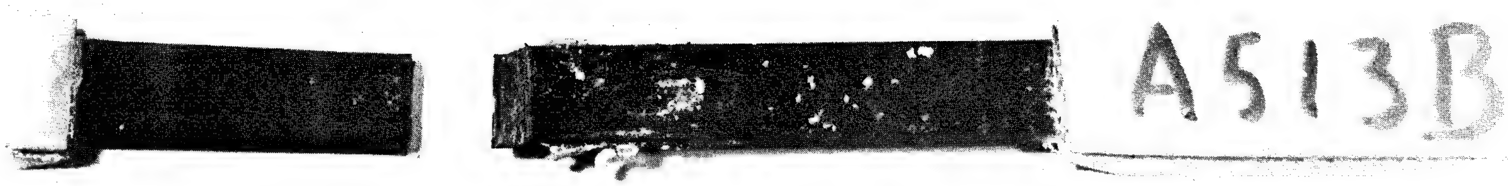


FIGURE II. 51 COMPRESSION INCREMENTAL LOADING SPECIMEN A5-13-B AFTER FAILURE, $[0/90_2/0]_{3T}$

APPENDIX II. 9

TENSILE FATIGUE

TABLE II.31

TENSILE FATIGUE - I, C-67

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtaulds HTS   Lam. Orient. $[0/90_2/0]_{3T}$

Matrix - ERL-2256   No. of Plies 12

Load Orient. 0^{o}

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☒F, Comp ☐, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: Standard Straight Sided Tensile Fatigue - I

Soak at Temp: -- °F for -- hr Test Temp. RT °F

Property		Panel No.	C-67							A&F	C&E	B&D
		Spec. Ident.	67-A	67-B(1)	67-C(1)	67-D(1)	67-E(1)	67-F(1)		Ave	Ave	Ave
Stress (ksi) - F, Cycles - N or	F_{mean}		10.70	16.62	30.55	20.40	30.45	10.45		10.58	30.50	18.51
	F_{min}		0.98	1.34	0.96	0.86	0.95	0.95		0.965	0.955	1.10
	F_{max}		20.50	31.90	60.00	40.00	59.9	20.00		20.25	59.95	35.95
	$N \times 10^{-6}$		8.1	0.134	0.01	0.021	0.005	10.101		9.1	0.075	0.0775
	R.S. F_{ult}		54.268	59.402	67.193	61.102	73.259	71.854		63.061	70.226	60.252
Modulus E, G x10⁻⁶	R.S. E or G (Primary)		11.189	11.423	12.042	11.750	12.010	11.589		11.389	12.026	11.586
	ν		0.0564	--	0.0700	0.0730	0.0795	--		0.0564	0.0748	0.0730
Stress, ksi or *Strain in./in.	Proportional Limit	F_{pl}	45.200	--	54.200	54.100	57.000(2)	--		45.200	55.600	54.100
		ϵ_1	0.00402	--	0.00448	0.00460	0.00460	--		0.00402	0.00454	0.00460
		ϵ_2	0.00019	--	0.00031	0.00033	0.00033	--		0.00019	0.00032	0.00033
	R.S. Ultimate	ϵ_1	0.00485	0.00520	0.00558	0.00520	0.00610	0.00620		0.00552	0.00584	0.00520
		ϵ_2	0.00016	--	0.00027	0.00032	0.000385	--		0.00016	0.00033	0.00032
		ϵ_{45}										
Specimen Width (in.)			0.492	0.502	0.503	0.503	0.502	0.502		0.497	0.502	0.502
Specimen Thick. (in.)			0.104	0.104	0.104	0.104	0.105	0.105		0.104	0.104	0.104

Strain Gage No. MM EA-03-250-BF-350, R.S. Testing only   Properties Based on

Extensometer B. Dualrange TSM D-1047   Nominal ☐; Actual ☒

Filament Count -- /in. Void Content 0.63 % Ply Thick. 0.0086 in.

Fil. Vol. Fract. 0.5634 Resin Wt. Fract. 0. -- Lam. Density 0.0552 lb/in.³

Laminate: Tape or Matrix Design Broadgoods-M. L. Tow Manuf. Fiberite

Balance Ply N/A Cure Spec SwRI S3-303

Organization: SwRI

Comments: 1,800 cycles/min; R≈+0.05; Tabs 181 glass/epoxy, Tab Adhesive - 3M AF-126-2.

(1) Failed during cycling by delamination of load tabs and in adhesive; new tabs bonded on for R.S. testing.

(2) A slight knee at 23.2 ksi was also observed.

*Indicates Strain Measurement by Resistance Strain Gages.

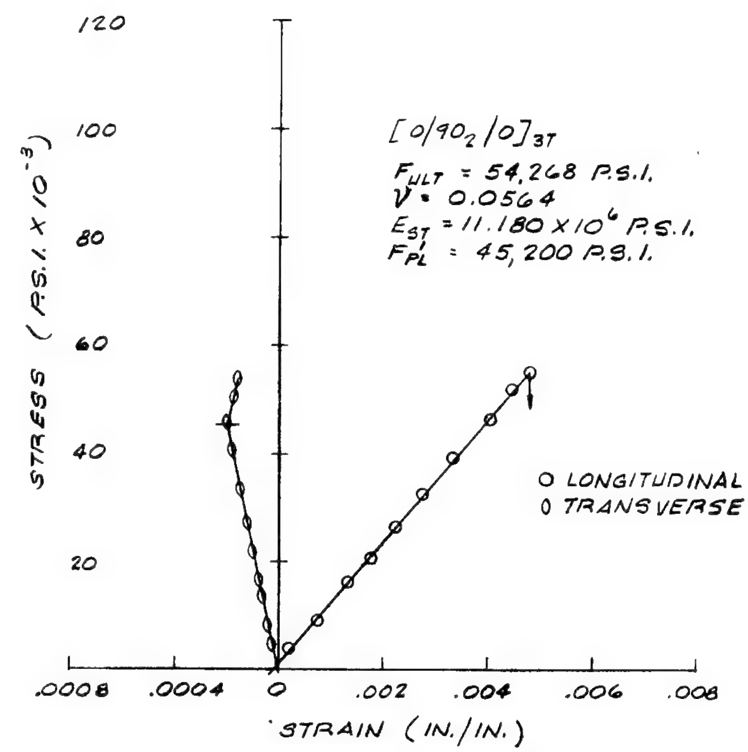


FIGURE II. 52. STRESS VS STRAIN,
SPECIMEN 67-A
(Fatigue/Tension)

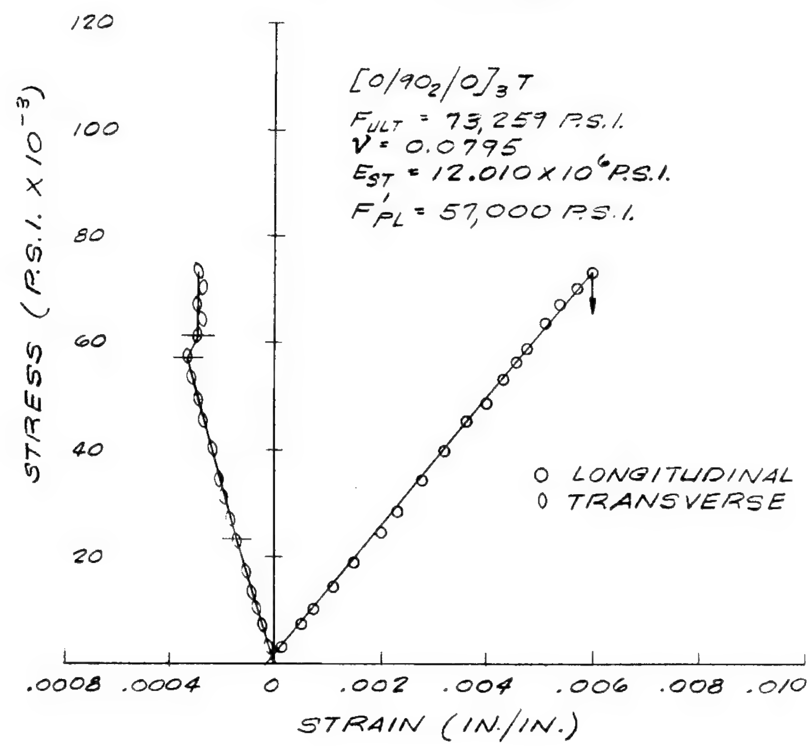


FIGURE II. 53. STRESS VS STRAIN,
SPECIMEN 67-E
(Fatigue/Tension)

TABLE II.32

TENSILE FATIGUE - II, C-57

FILAMENTARY LAMINATE STATIC PROPERTY DATA (ORGANIC MATRIX)

Material System: Fiber - Courtauld's HTS — Lam. Orient. $[0/90_2/0]_{3T}$

Matrix - ERL-2256 — No. of Plies 12

Load Orient. 0^o

Balance Ply Added: Yes ☐ No ☒

Loading Type: Tension ☒ F, Comp ☐, Shear ☐ Interlam. Shear ☐

Longitudinal Flexure ☐, Transverse Flexure ☐

Type Test Specimen: Standard Straight Sided Tensile Fatigue - II

Soak at Temp: -- °F for -- hr Test Temp. RT °F

Property	Panel No. / Spec. Ident.	C-57 T-57B[1]	T-57C[1]	T-57D	T-57E[2]	T-57F	T-57G[3]		B-C Ave	D&F Ave	E&G Ave[2,3]
Stress (ksi)-F or N Cycles	F Mean	20.40	20.60	10.30	9.92	10.30	10.30		20.50	10.30	10.11
	F Min	0.78	0.79	0.40	0.38	0.40	0.40		0.785	0.40	0.39
	F Max	39.80	40.45	20.20	19.45	20.20	20.20		40.12	20.20	19.82
	$N \times 10^{-6}$	0.056	0.028	10.531	10.288	10.113	10.588		0.042	10.322	10.438
	R.S. F_{ult}	--	--	55.063	56.378	77.347	70.888		--	63.705	63.633
Modulus $E, G \times 10^{-6}$	ESI (Primary)	--	--	11.766	10.790	12.104	12.889		--	11.935	11.840
	ν	--	--	0.0742	0.0595	0.0573	0.0617		--	0.0658	0.0606
Stress, ksi or *Strain in./in.	Proportional Limit (Transverse) F_{p1}	--	--	41.000	--	55.000	55.000		--	48.000	55.000
	ϵ_1	--	--	0.00351	--	0.00468	0.00450		--	0.00410	0.00450
	ϵ_2	--	--	0.00025	--	0.00026	0.00250		--	0.00026	0.00250
	Ultimate ϵ_1	--	--	0.00468	0.00622	0.00639	0.00550		--	0.00553	0.00586
	ϵ_2	--	--	0.00031	0.00031	0.00022	0.00029		--	0.00036	0.00030
	ϵ_{45}										
Specimen Width (in.)		0.751	0.751	0.751	0.757	0.751	0.750		0.751	0.751	0.754
Specimen Thick. (in.)		0.102	0.101	0.101	0.104	0.101	0.101		0.102	0.101	0.102

Strain Gage No. EA-03-250-BF-350 } Residual Str. Test only — Properties Based on

Extensometer B. Dualrange TSM D-1047 — Nominal ☐; Actual ☒

Filament Count -- /in. Void Content 0.92 % Ply Thick. 0.0088 in.

Fil. Vol. Fract. 0.5661 Resin Wt. Fract. 0. -- Lam. Density 0.0551 lb/in.³

Laminate: Tape or Matrix Design Broadgoods-M. L. Manuf. Fiberite

Balance Ply N/A Tow Cure Spec SwRI S3-303

Organization: SwRI

Comments: 1800 cycles/min; R≈0.05 Tabs 181 Glass/epoxy. Tab Adhesive: 3M AF-126-2

(1) Failed in Tab adhesive bond and subsequent specimen delamination under tab area. Specimen damaged such that retest not possible.

*Indicates Strain Measurement by Resistance Strain Gages.

(2) Specimen preloaded to 24.8 ksi then fatigue tested as indicated.

(3) Specimen preloaded to 25.8 ksi then fatigue tested as indicated.

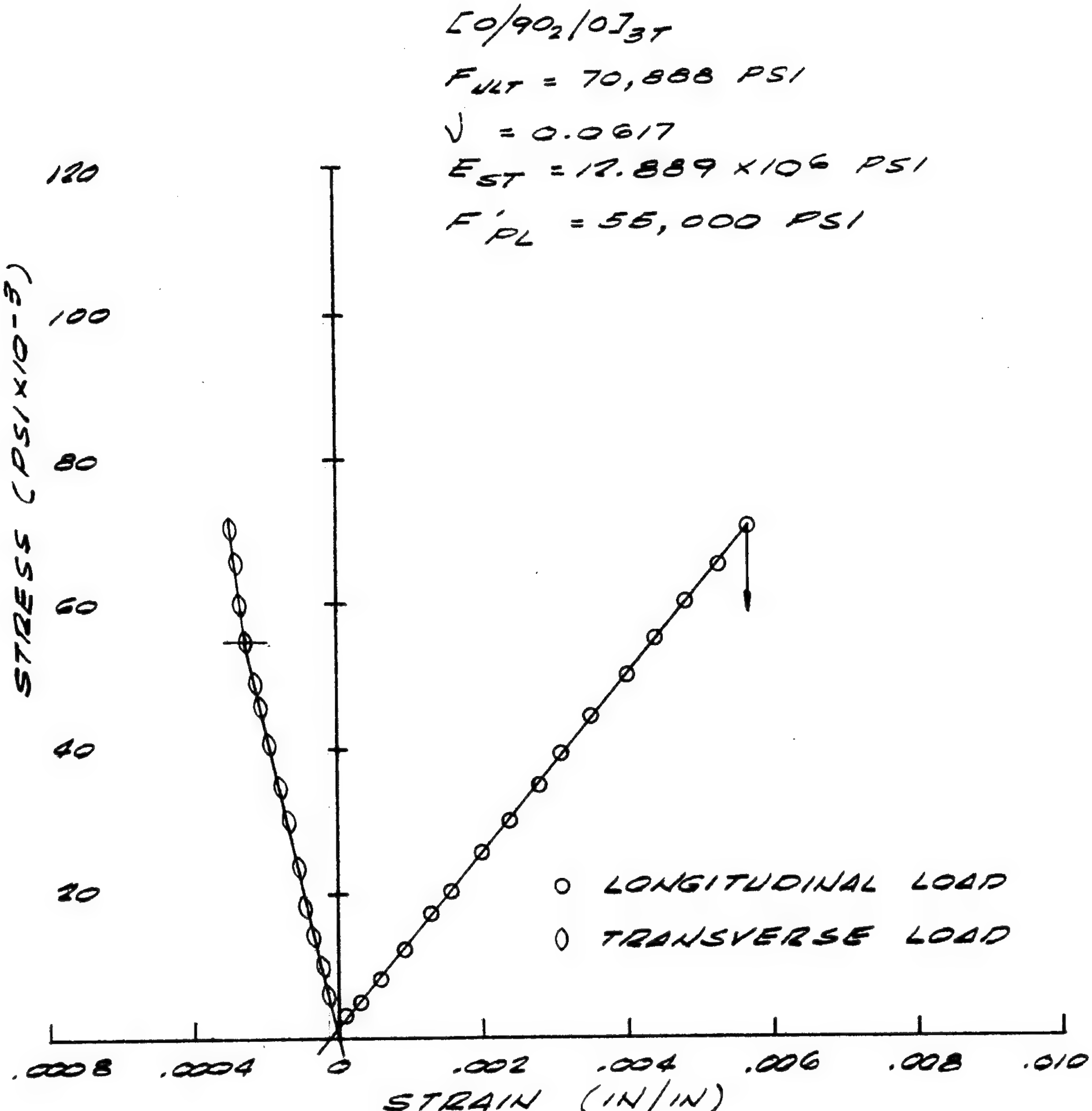


FIGURE II.54 STRESS VS STRAIN, SPECIMEN T-57-G
(Tension Fatigue/Tension)

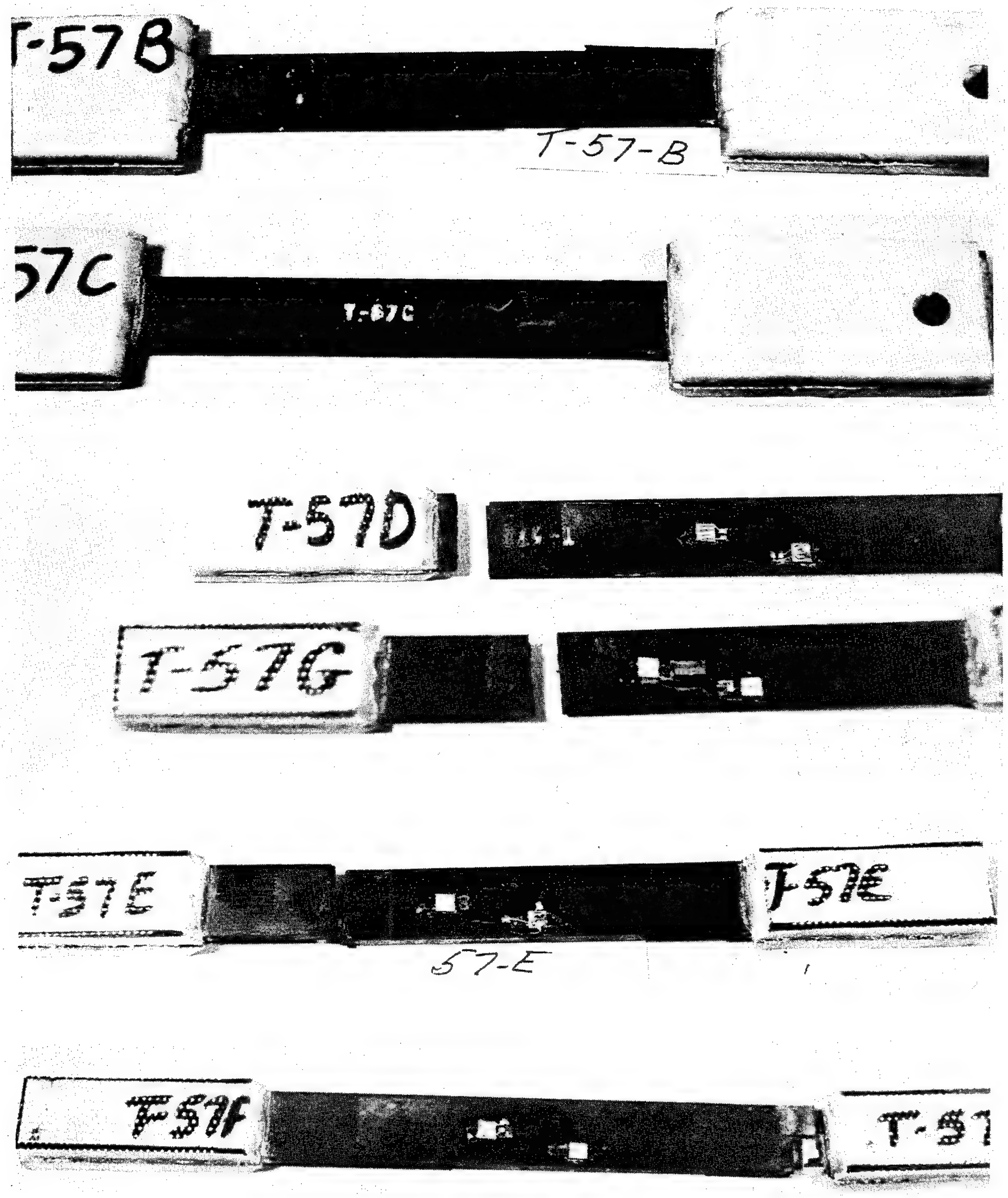


FIGURE II.55. TENSILE SPECIMENS T-57-B, C, D, E, F, G AFTER FAILURE (FATIGUE OR RESIDUAL STRENGTH), $[0/90_2/0]_{3T}$

APPENDIX III

DETAILED EXPERIMENTAL DATA ON TUBES

This Appendix includes detailed data on the physical properties of the tubular specimens, as well as stress-strain data and photographs of the tube failure modes.

The following comments are pertinent to the stress-strain descriptions of tubes CT-16, 43, and 48:

CT-16

During the biaxial loading test of this specimen, in which the loading was combined tension/torsion, a hysteresis effect was noted in the $\tau_{x\theta}$-$\gamma_{x\theta}$ path, which was very similar to those generated in pure torsion tests. The shear modulus computed from the combined load test was the same as that computed from the pure torsion test on this material (0.535×10^6 psi), indicating no coupling between the axial load and torsional response, at stresses within the proportional limit. A coupling effect was noted, however, in which a purely torsional load (within the proportional limit) created a compressive axial strain and a tensile hoop strain. In magnitude these strains were, respectively, 0.0085 and 0.0058 of the shear strain.

CT-43

Instrumentation limitations did not allow accurate strain measurements of $\gamma_{x\theta}$ at large values. It was therefore necessary to extrapolate to higher strains (longer times), which resulted in fictitiously higher values of $\gamma_{x\theta}$ than actually prevailed. The stress-strain data shown are valid out to about 3%, but beyond that the strain is exaggerated.

CT-48

On the initial loading path longitudinal cracks developed at point a, shifting the strain to point b. Continued loading carried the specimen to point c, at which the load capacity of the machine was reached. Unloading was linear from c to the origin. The specimen was then reloaded in a higher capacity facility, behaving linearly to failure at 98 ksi.

TABLE III. 1

TUBE PHYSICAL DATA

Spec. No.	Layup	Process Code*	Avg. Wall Thickness (in.)	Avg. O.D. (in.)	Fiber Volume (%)	Void Volume (%)	Density (lb/in^2)	Grip Type**
CT-7	$[0]_{4T}$	PD	0.0591	1.068	42.34	0.65	0.0524	SS
9	$[0]_{4T}$	PD	0.0431	1.107	47.93	0.41	0.0536	F/E W
14	$[0]_{4T}$	PD	0.0456	1.106	54.96	0.35	0.0550	SS
15	$[0]_{4T}$	PD	0.0472	1.104	47.51	0.44	0.0536	SS
16	$[0]_{4T}$	PD	0.0474	1.112	47.81	0.45	0.0533	SS
17	$[0]_{4T}$	PD	0.0490	1.003	45.55	1.95	0.0523	SS
37	$[0]_{8T}$	SP-1	0.1008	1.094	50.70	0.78	0.0540	(End Plugs Only)
38	$[0]_{8T}$	SP-2	0.0854	1.085	52.65	0.50	0.0545	SS
39	$[0]_{8T}$	SP-2	0.0872	1.080	52.00	0.78	0.0542	SS
41	$[0]_{8T}$	SP-2	0.0774	1.070	55.01	0.73	0.0549	SS
42	$[0/90_2/0]_T$	SP-2	0.0386	1.090	51.09	0.99	0.0540	SS
43	$[0/90_2/0]_T$	SP-2	0.0362	1.090	51.02	1.13	0.0538	SS
44	$[0/90_2/0]_{2T}$	SP-2	0.0836	1.084	53.22	2.15	0.0537	SS
45	$[0]_{4T}$	SP-2	0.0436	1.072	56.22	0.77	0.0551	S F/E
46	$[0]_{8T}$	SP-2	0.0804	1.089	53.78	0.74	0.0546	SS
48	$[0]_{4T}$	SP-2	0.0421	1.073	50.92	0.58	0.0540	SS
49	$[0/90_2/0]_T$	SP-2	0.0605	1.085	46.16	2.30	0.0522	SS
51	$[0/90_2/0]_T$	SP-2	0.0402	1.093	53.52	0.68	0.0546	SS
53	$[0/90_2/0]_T$	SP-2	0.0436	1.044	47.60	0.54	0.0535	SS
57	$[0/90_2/0]_T$	SP-2	0.0411	1.092	49.92	1.14	0.0536	SS
59	$[0/90_2/0]_T$	SP-2	0.0412	1.091	53.20	1.52	0.0539	SS

*PD = Process Development
SP-1 = Std. Process #1 (I.D. bleed only)
SP-2 = Std. Process #2 (I.D. & O.D. bleed)

**F/E W = Fiberglass/Epoxy Wrap Tabs
S F/E = Segmented Fiberglass/Epoxy Tabs
SS = Segmented Steel Tabs

TABLE III.2

SUMMARY OF STRESS-STRAIN DATA

Spec No.	Proportional Limit σ_x	σ_θ	$\tau_{x\theta}$	ϵ_x	ϵ_θ	$\gamma_{x\theta}$	Ultimate σ_x	σ_θ	$\tau_{x\theta}$	ϵ_x	ϵ_θ	$\gamma_{x\theta}$
CT-7	-49.83	--	--	-0.315	0.209	--	-87.56	--	--	-0.580	0.495	--
9	--	--	1.00	--	--	0.155	--	--	10.5	--	--	4.30
14	22.00	--	--	0.120	--	--	89.00	--	--	0.450	--	--
15	--	--	--	--	--	--	--	0.570	--	--	--	--
16	--	--	1.00	--	--	0.187	--	--	7.57	--	--	2.39
17	2.70	--	6.80	0.010	-0.0235	2.700	6.02	--	6.80	-0.006	-0.052	2.70
37	--	2.86	--	-0.0054	0.251	--	--	2.86	--	-0.0054	0.251	--
38	55.00	--	--	0.258	-0.133	--	68.00	--	--	0.320	-0.153	--
39	3.99	3.77	--	0.0206	0.322	--	3.99	3.77	--	0.0206	0.322	--
41	-70.42	--	--	-0.328	0.103	--	-134.40	--	--	-0.653	0.220	--
42	-6.59	5.45	--	-0.0815	0.0338	--	-6.59	5.45	--	-0.0815	0.0338	--
43	--	--	1.00	--	--	0.065	--	--	11.9*	-0.300	-0.300	7.30*
44	-50.74	--	--	-0.483	0.0243	--	-66.62	--	--	-0.848	0.0474	--
45	67.00	--	--	0.305	--	--	67.00	--	--	0.305	--	--
46	-2.59	2.50	--	-0.0091	0.155	--	-2.59	2.50	--	-0.0091	0.155	--
48	46.30	--	--	0.228	-0.071	--	98.00	--	--	0.405	-0.128	--
49	37.60	37.20	--	0.606	0.305	--	37.60	37.20	--	0.606	0.305	--
51	16.00	--	2.00	0.120	-0.065	0.310	25.20	--	11.9	0.188	-0.150	4.00
53	--	4.23	--	0.0070	0.0422	--	--	28.68	--	0.0250	0.310	--
57	40.00	--	--	0.0385	-0.030	--	55.40	--	--	0.515	-0.038	--
59	-49.26	--	--	-0.530	0.080	--	-56.37	--	--	-0.655	0.160	--

Notes: All stresses in ksi, strains in %.
Strain values averages of 2 or 3 gages.

*Failure state

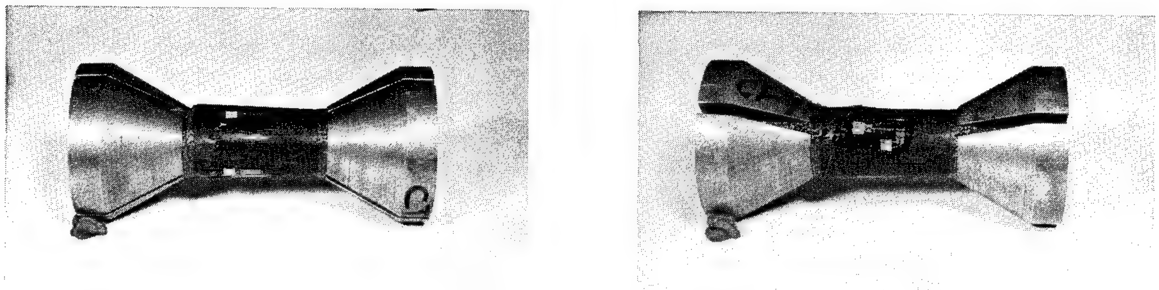
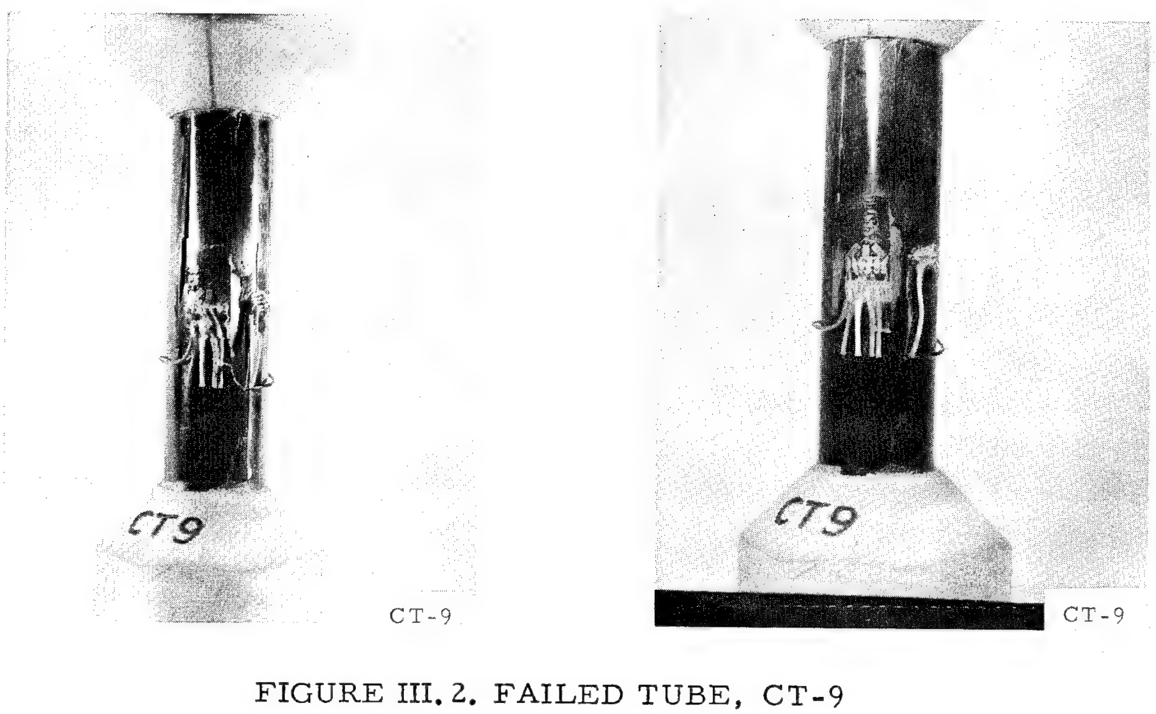


FIGURE III. 1. FAILED TUBE, CT-7



CT-9 CT-9

FIGURE III. 2. FAILED TUBE, CT-9

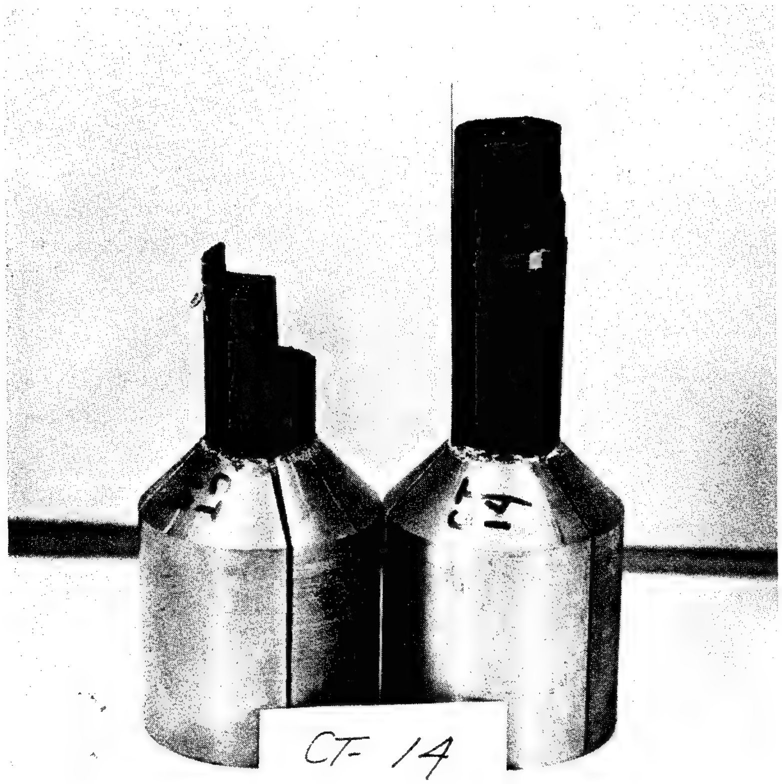


FIGURE III. 3. FAILED TUBE, CT-14

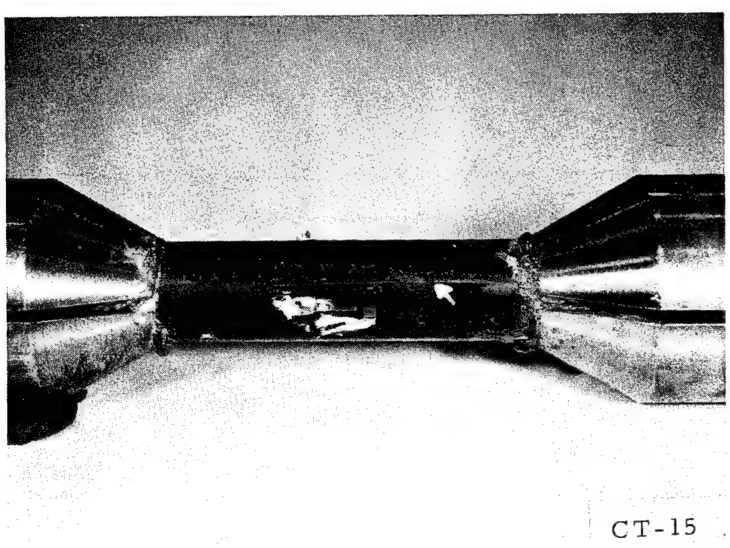


FIGURE III. 4. FAILED TUBE, CT-15

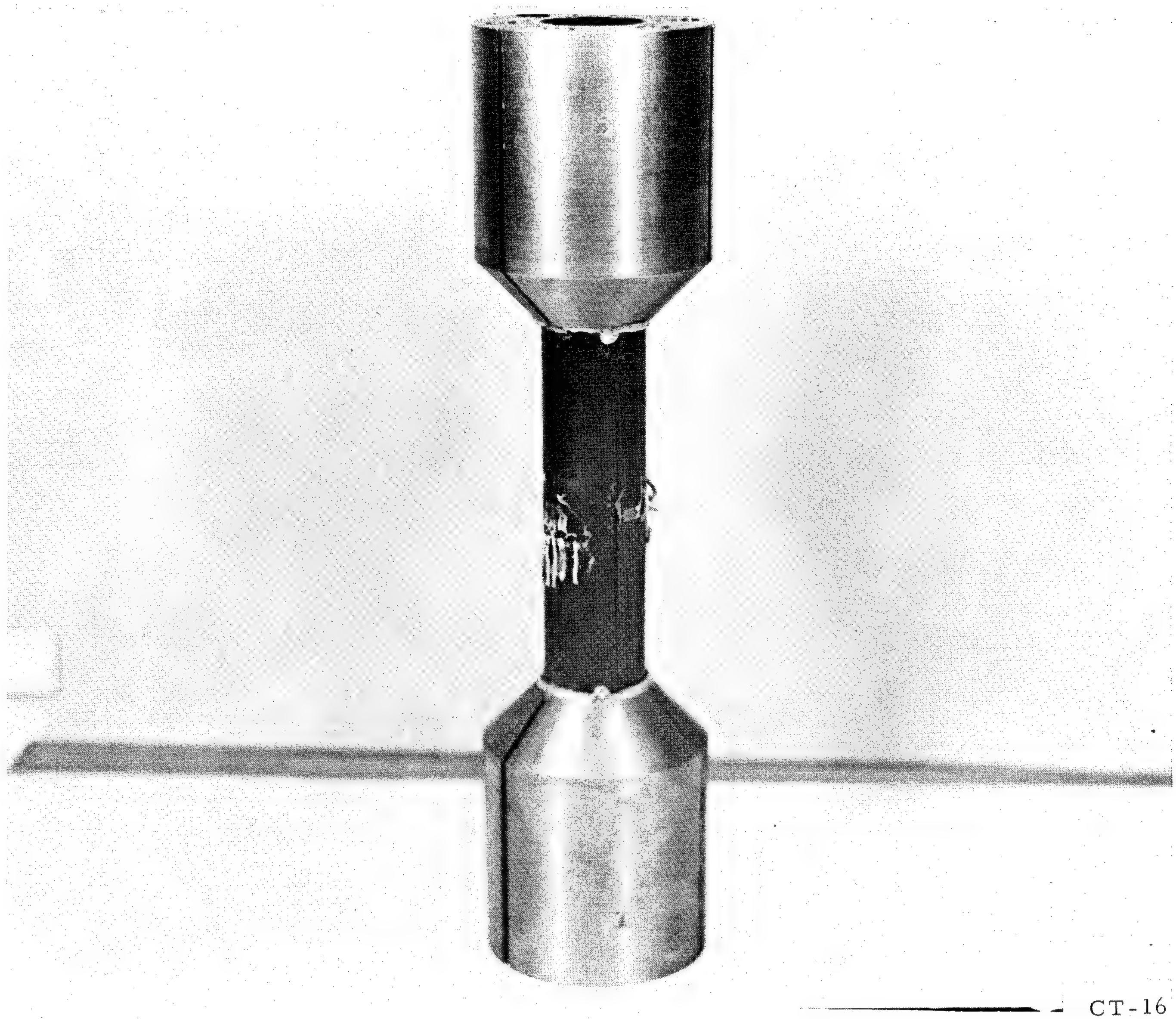


FIGURE III.5. FAILED TUBE, CT-16

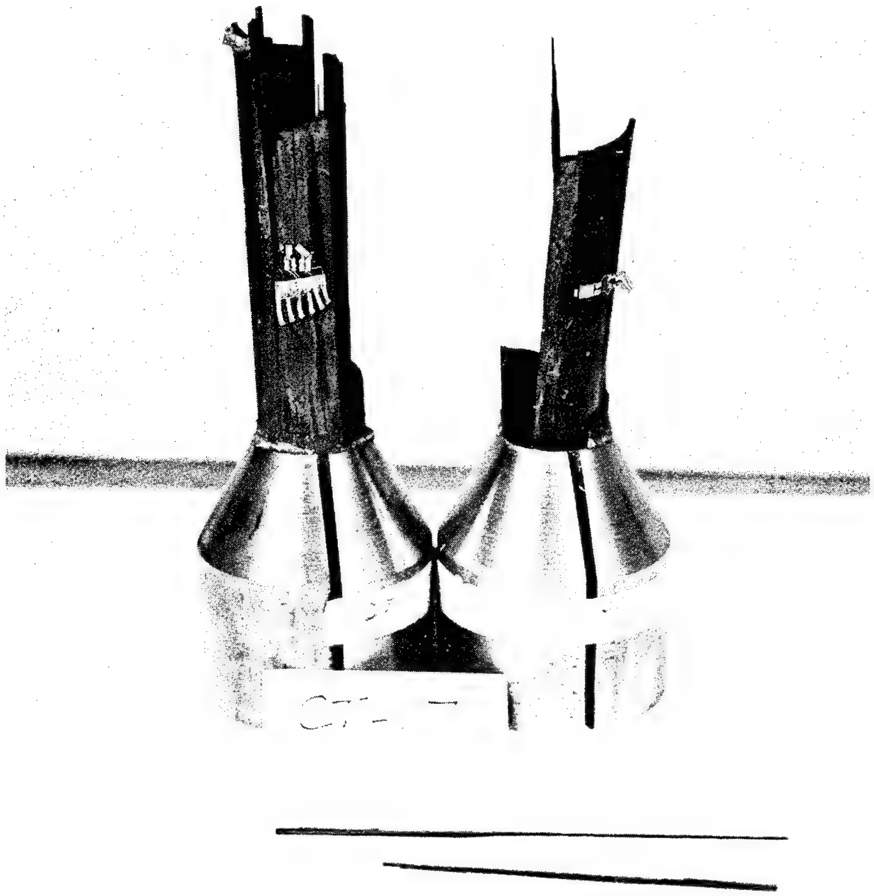
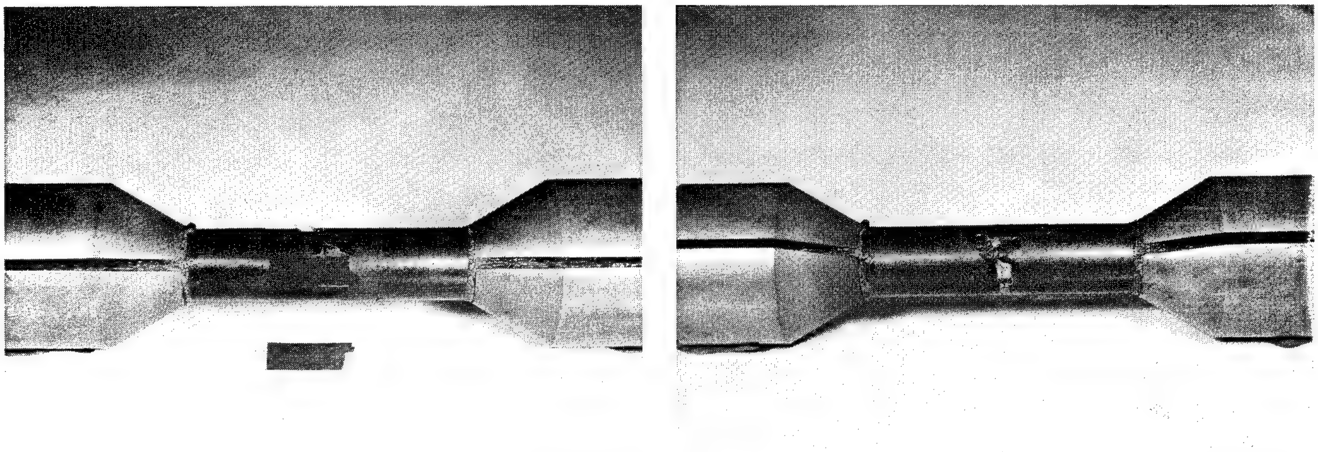


FIGURE III. 6. FAILED TUBE, CT-17

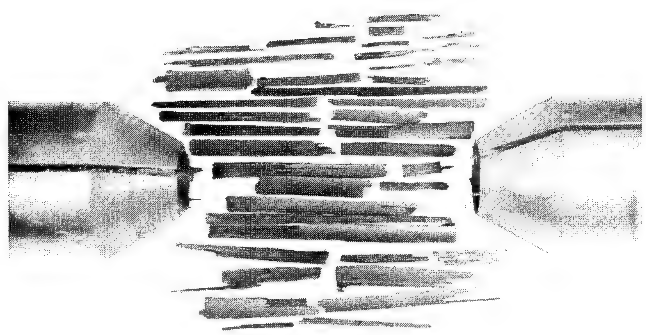
CT-37

FIGURE III. 7. FAILED TUBE, CT-37



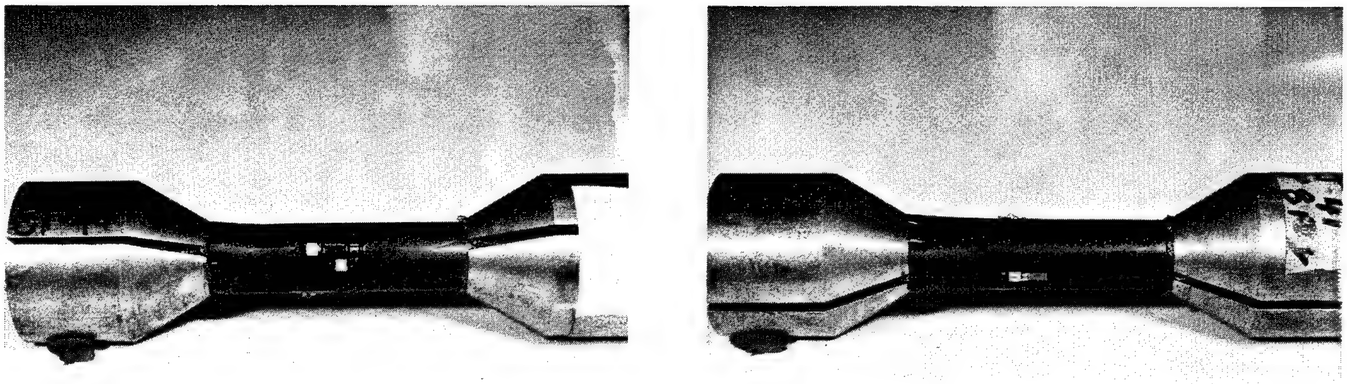
CT-38 CT-38

FIGURE III. 8. FAILED TUBE, CT-38



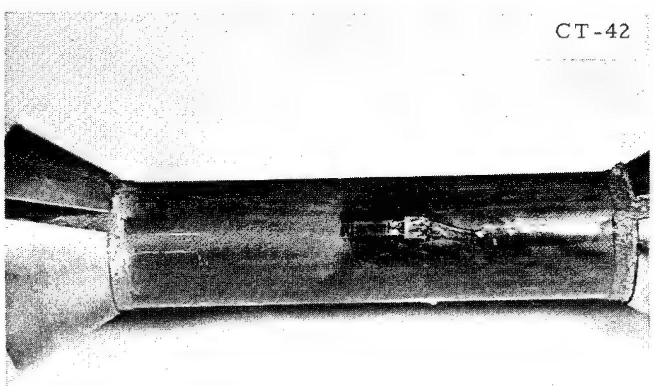
CT-39

FIGURE III. 9. FAILED TUBE, CT-39



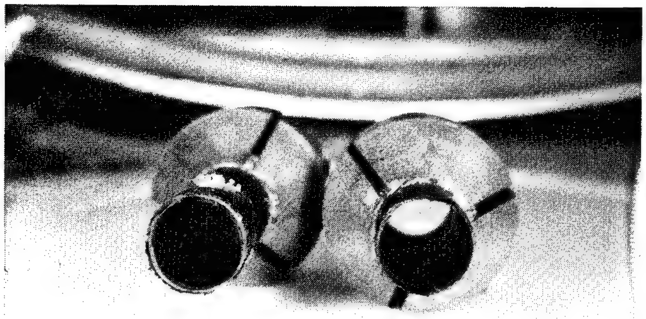
CT-41 CT-41

FIGURE III. 10. FAILED TUBE, CT-41

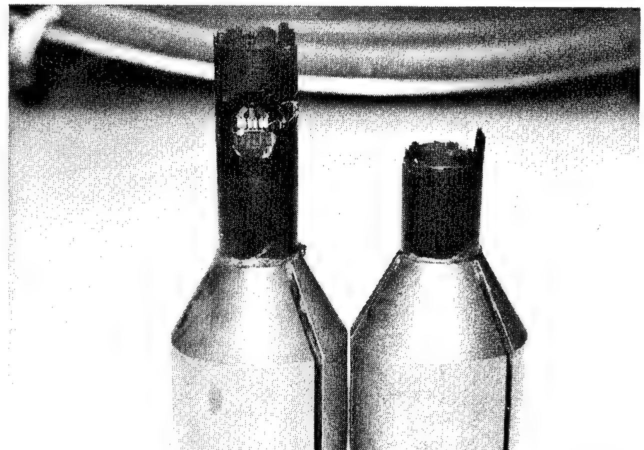


CT-42

FIGURE III. 11. FAILED TUBE, CT-42

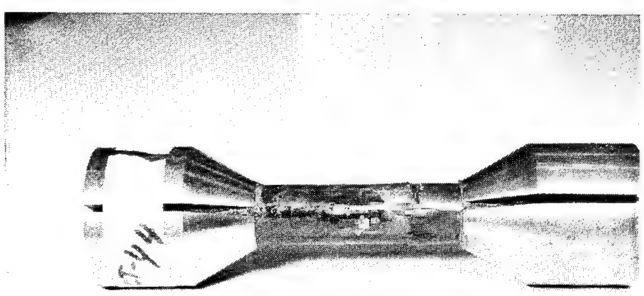


CT-43

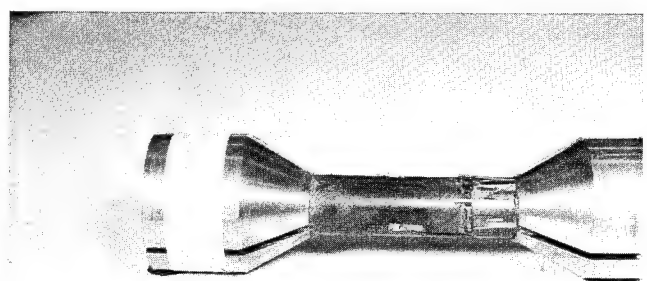


CT-43

FIGURE III.12. FAILED TUBE, CT-43



CT-44



CT-44

FIGURE III.13. FAILED TUBE, CT-44

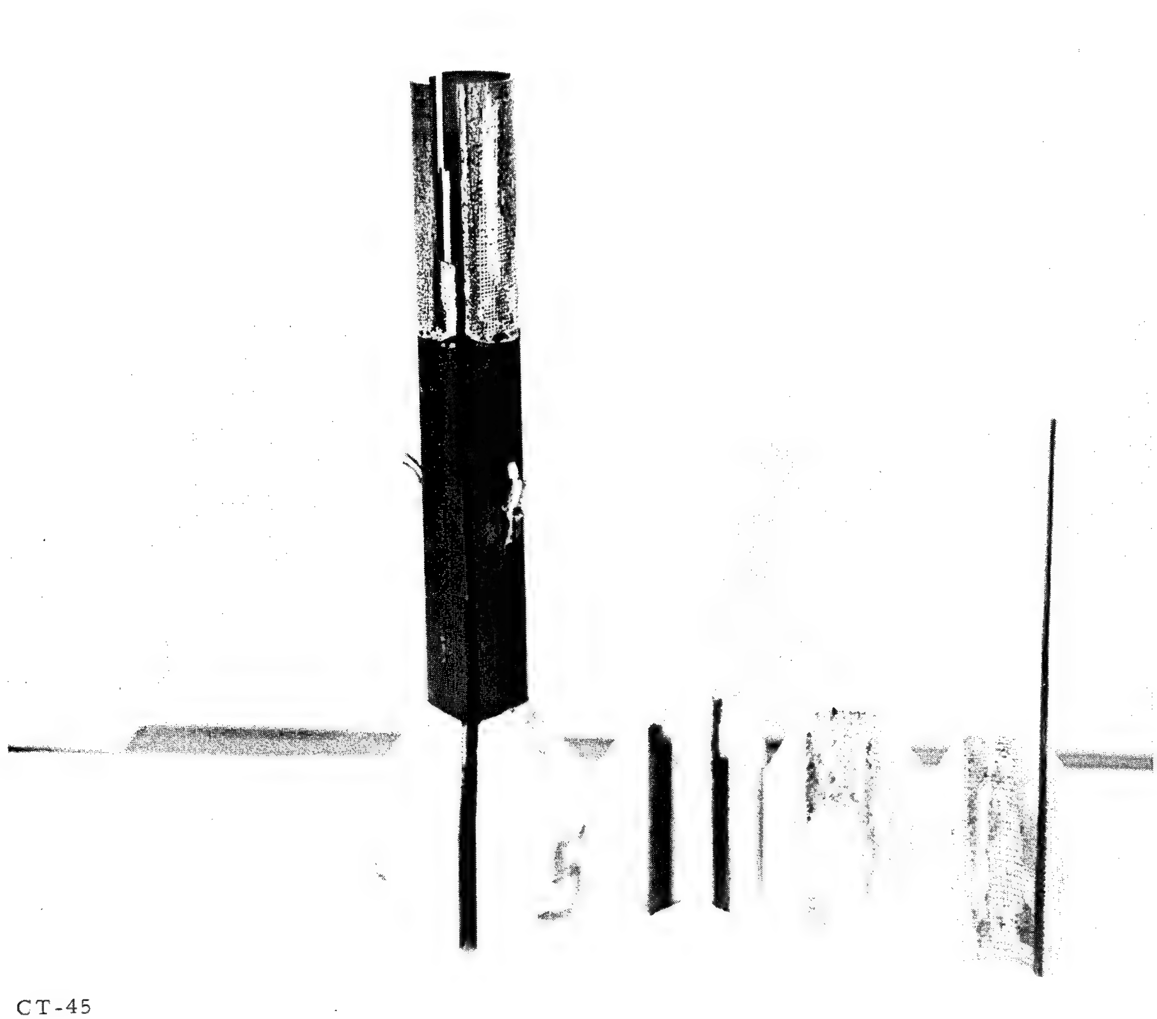


FIGURE III. 14. FAILED TUBE, CT-45

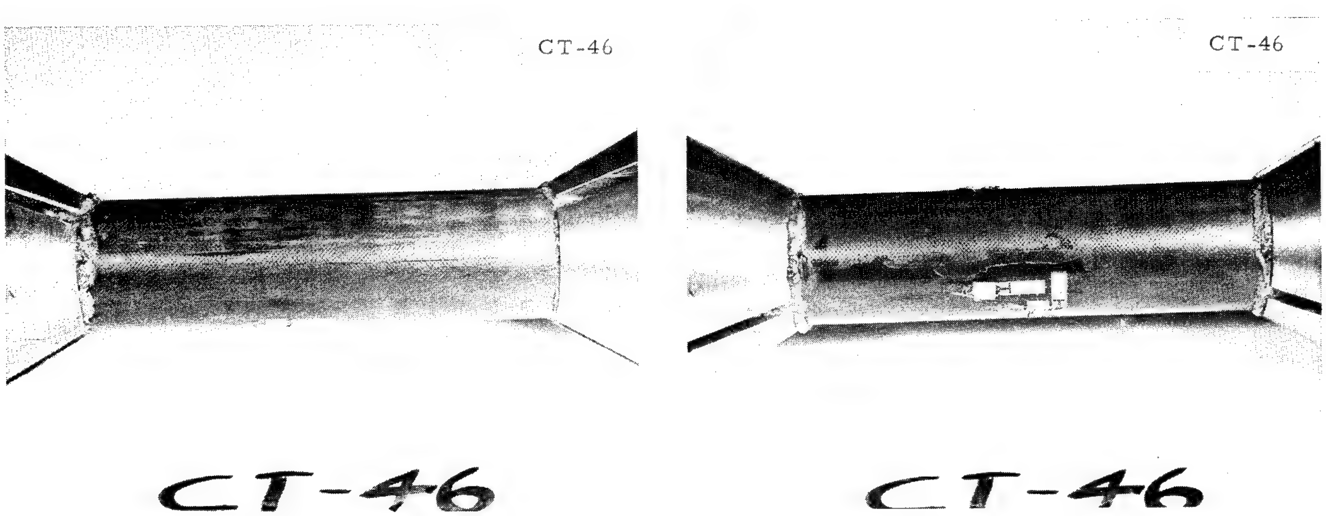


FIGURE III. 15. FAILED TUBE, CT-46

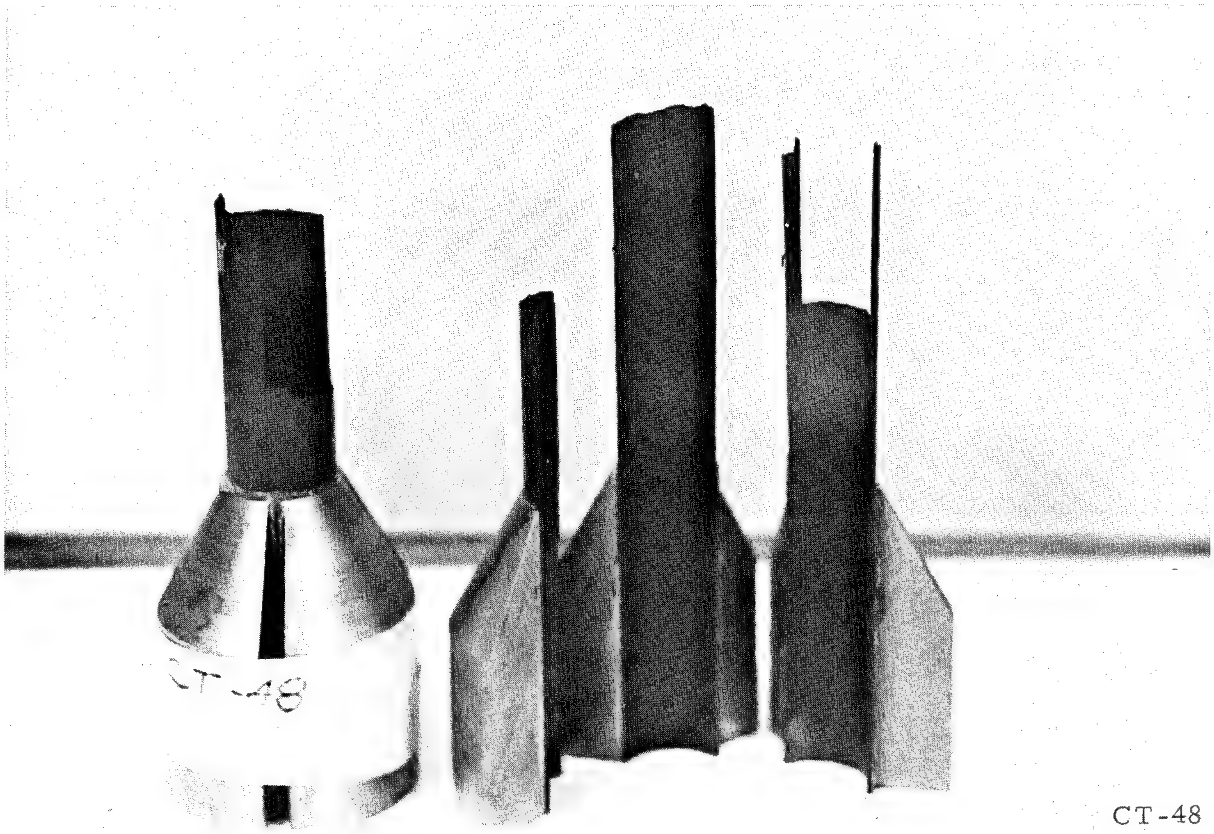


FIGURE III. 16. FAILED TUBE, CT-48

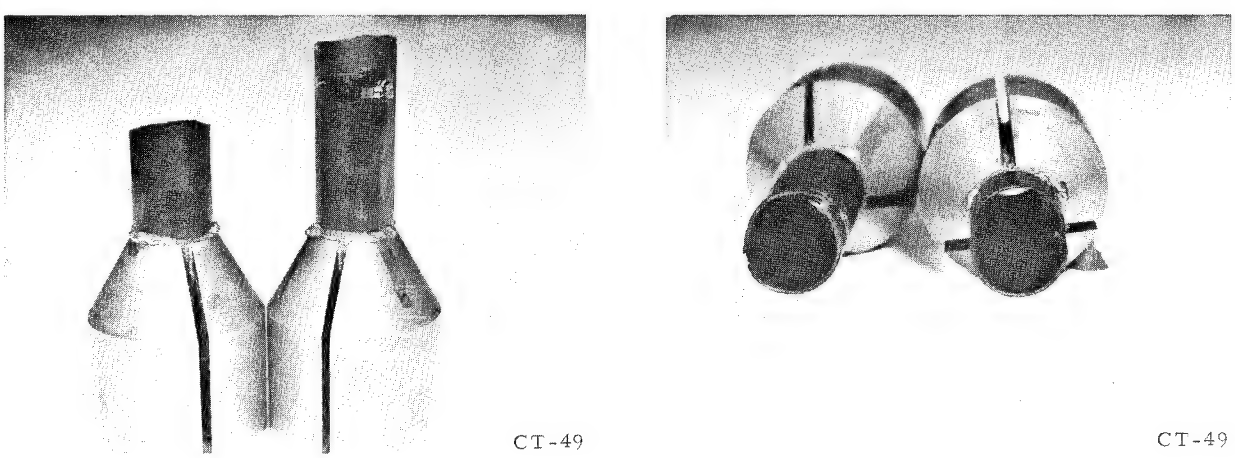


FIGURE III. 17. FAILED TUBE, CT-49

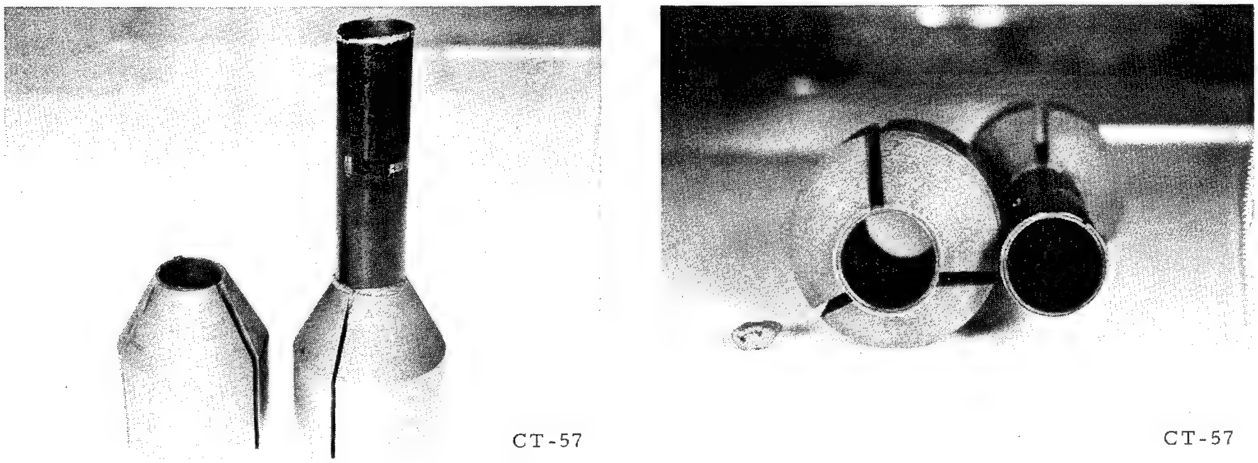


FIGURE III.20. FAILED TUBE, CT-57

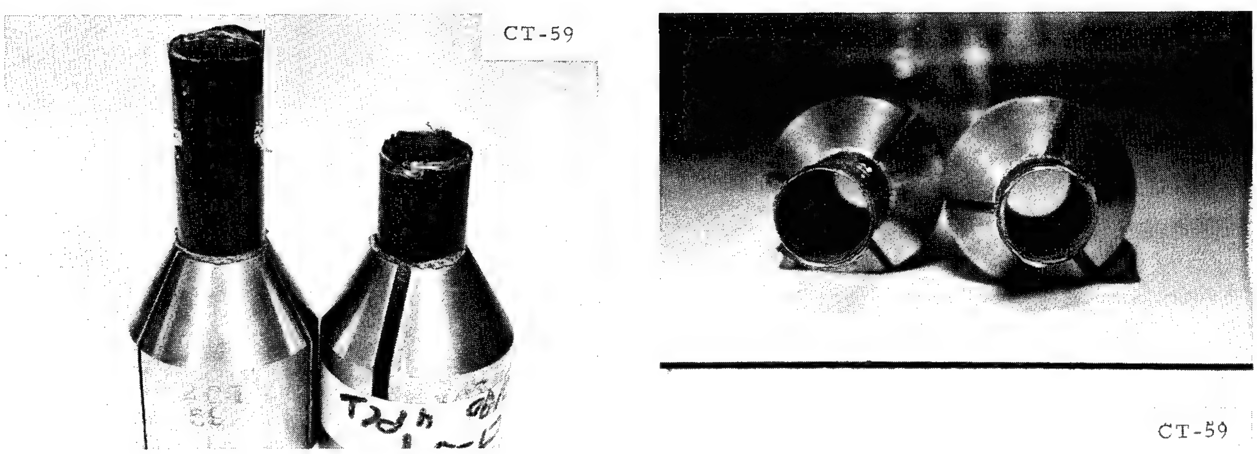
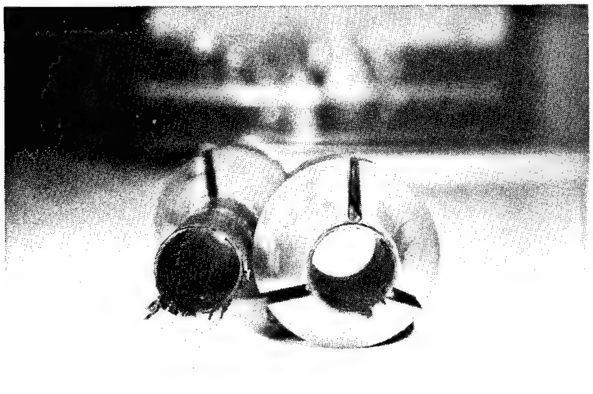


FIGURE III.21. FAILED TUBE, CT-59



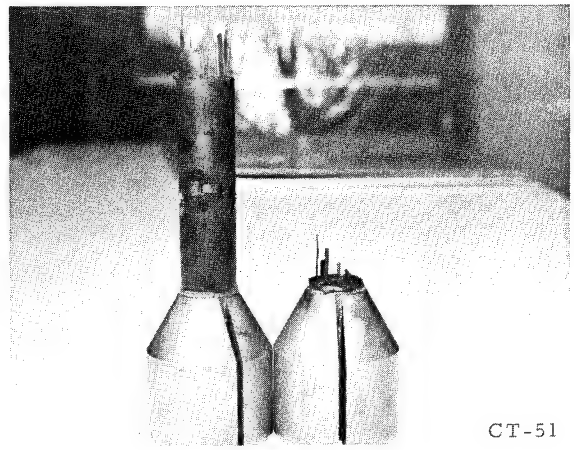
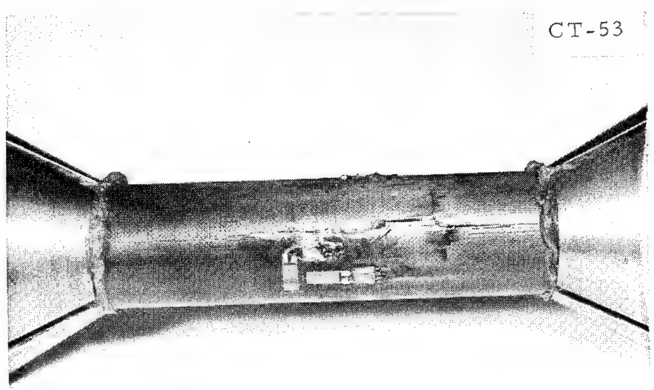


FIGURE III. 18. FAILED TUBE, CT-51



CT-53

FIGURE III. 19. FAILED TUBE, CT-53

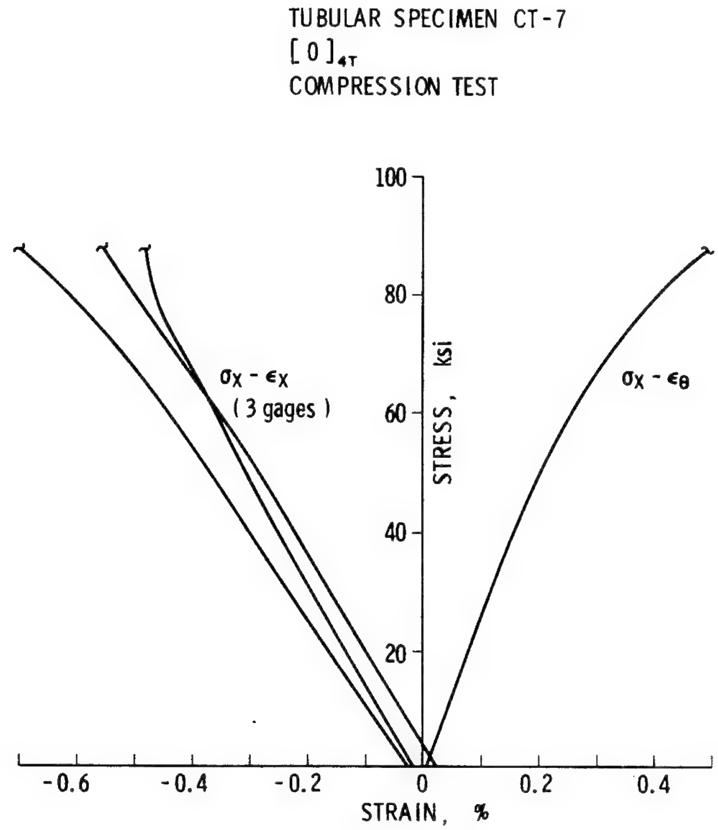


FIGURE III.22. STRESS-STRAIN CURVE, CT-7

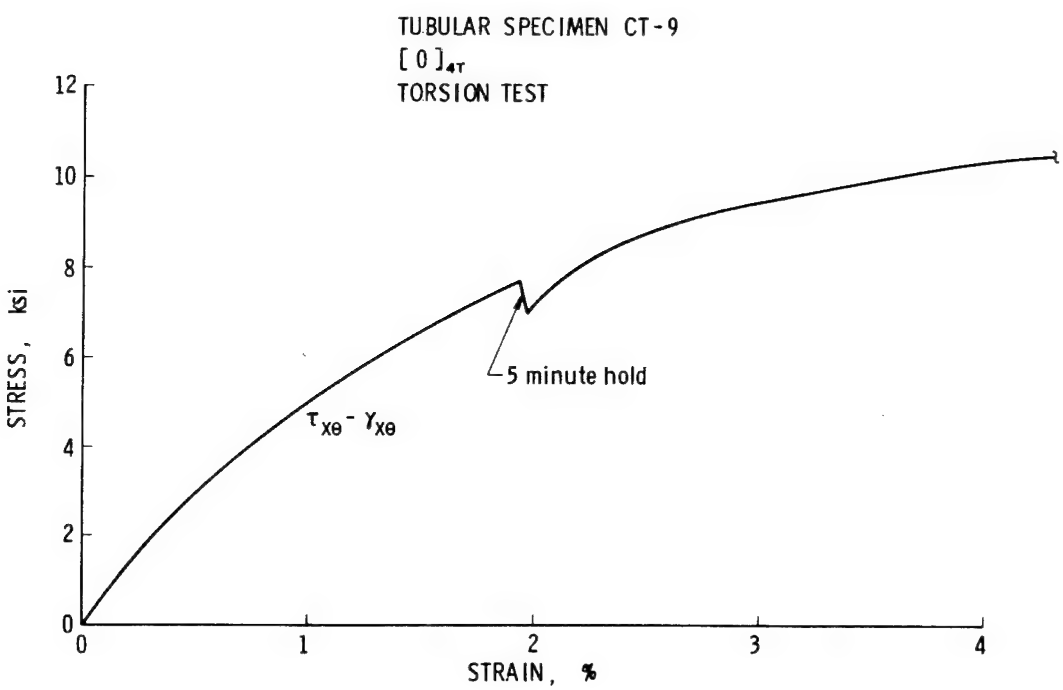


FIGURE III.23. STRESS-STRAIN CURVE, CT-9

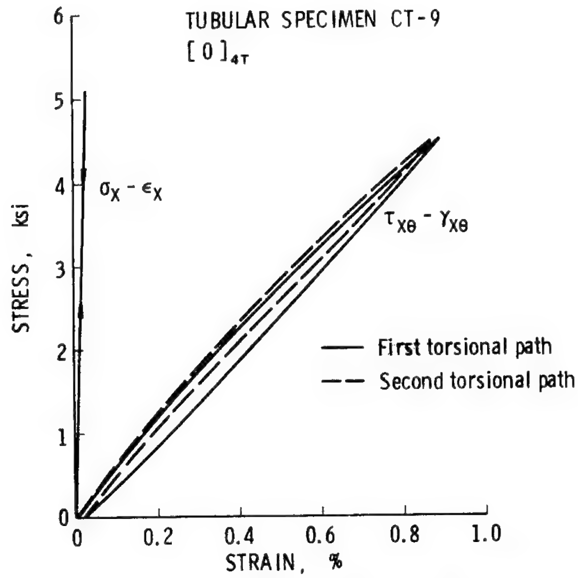


FIGURE III.24. STRESS-STRAIN CURVE, CT-9

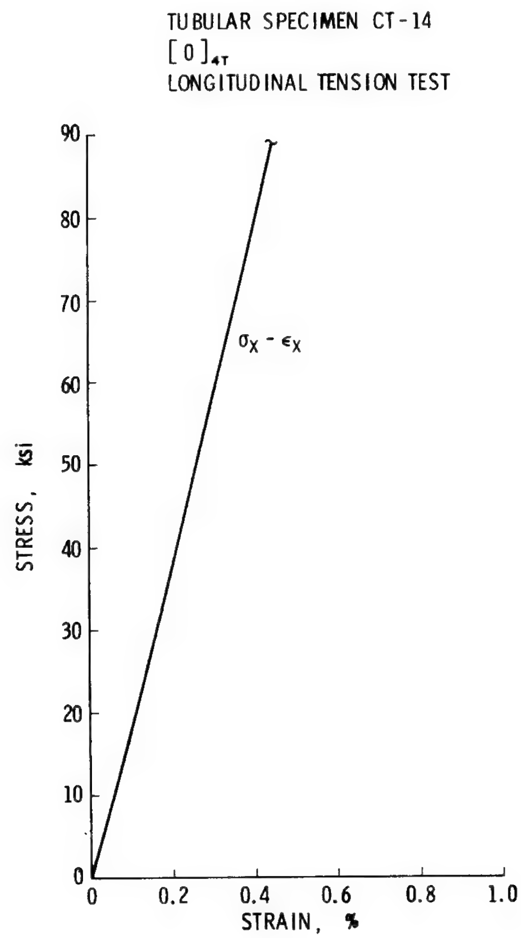


FIGURE III.25. STRESS-STRAIN CURVE, CT-14

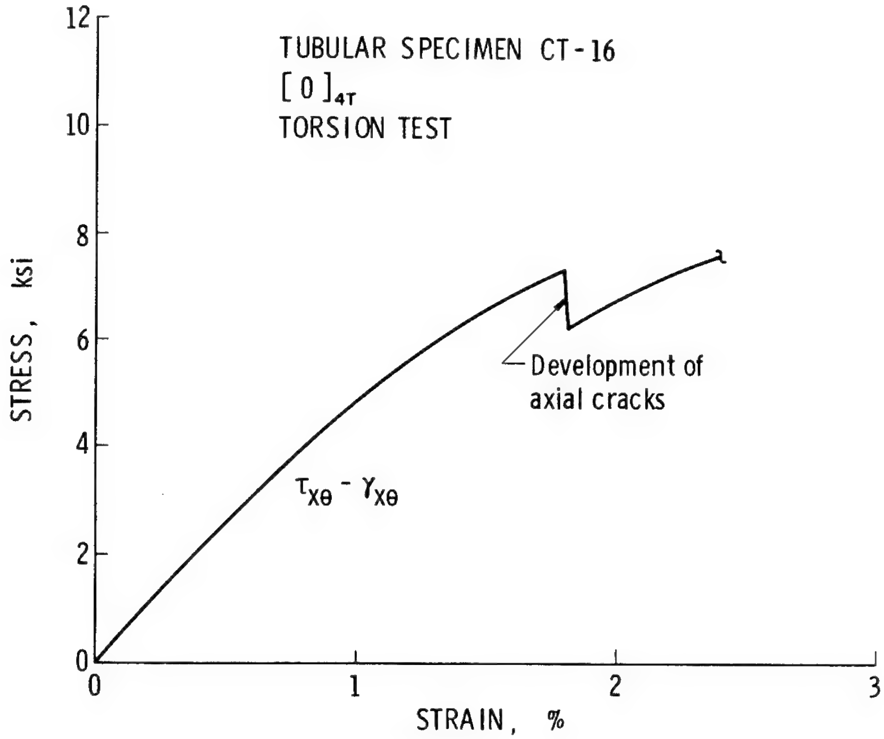


FIGURE III. 26. STRESS-STRAIN CURVE, CT-16

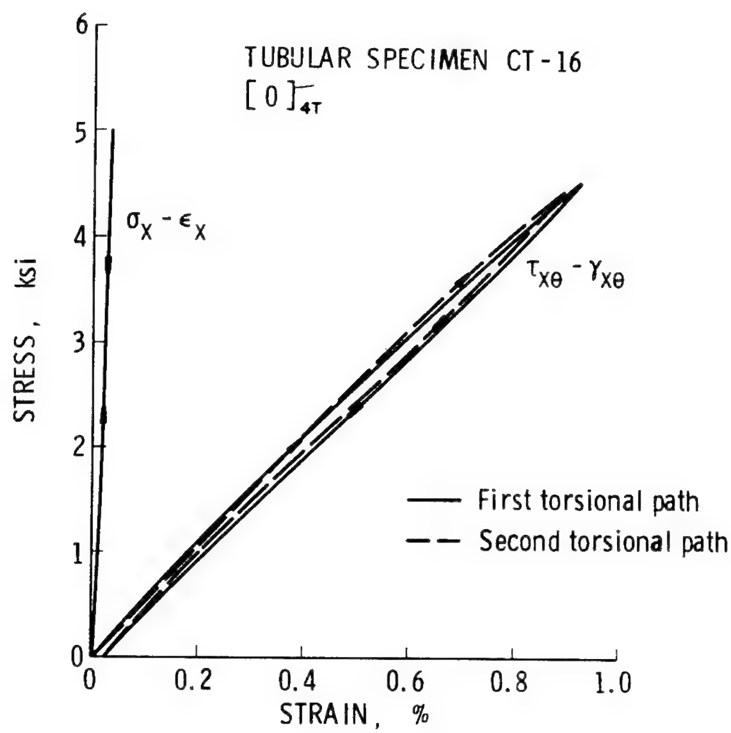


FIGURE III. 27. STRESS-STRAIN CURVE, CT-16

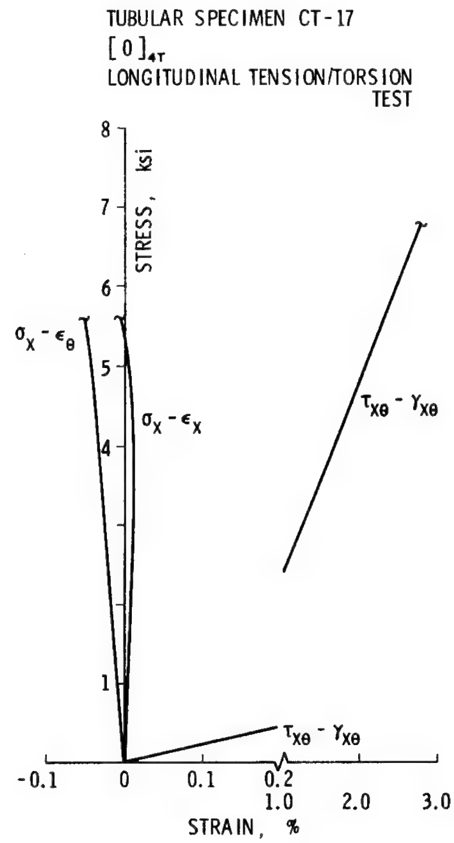


FIGURE III. 28. STRESS-STRAIN CURVE, CT-17

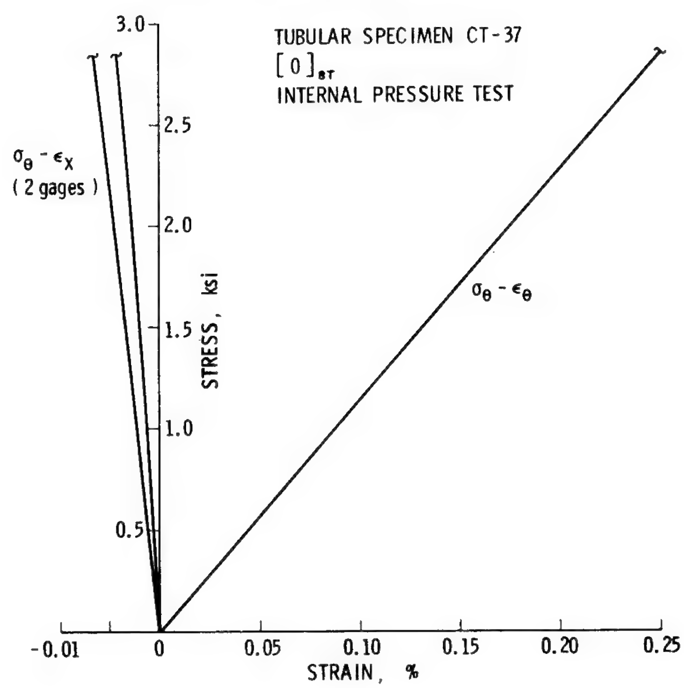


FIGURE III. 29. STRESS-STRAIN CURVE, CT-37

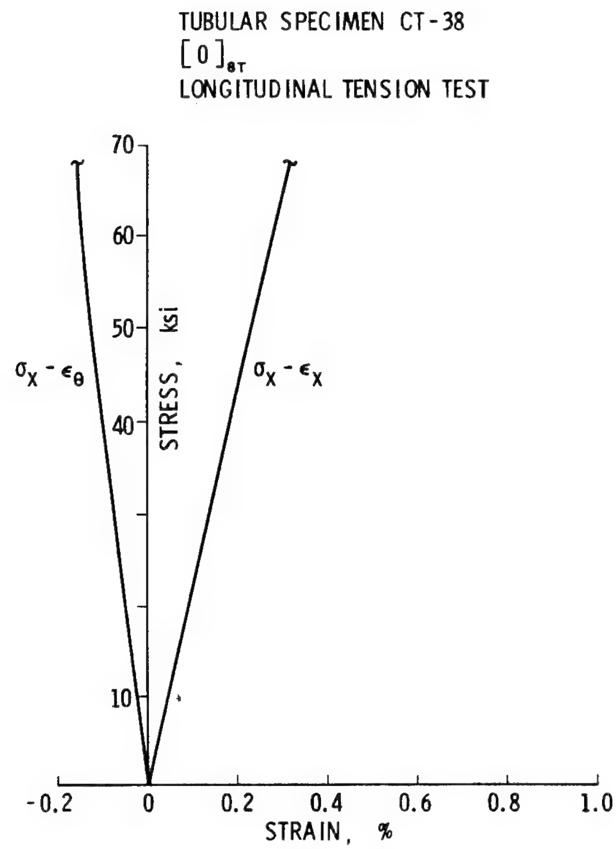


FIGURE III. 30. STRESS-STRAIN CURVE, CT-38

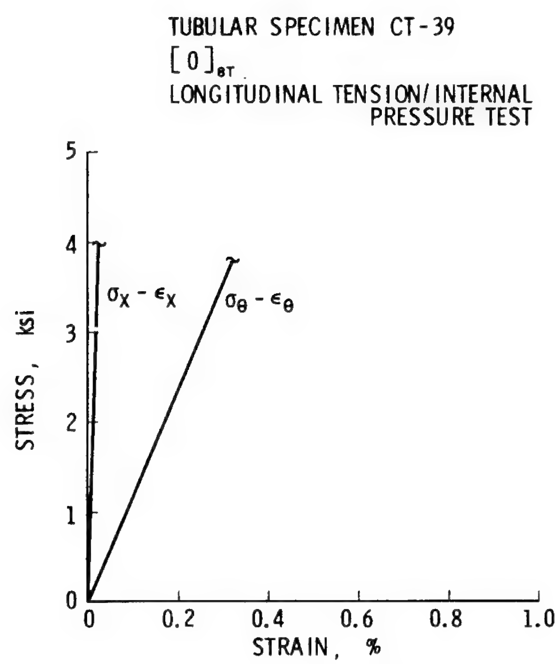


FIGURE III. 31. STRESS-STRAIN CURVE, CT-39

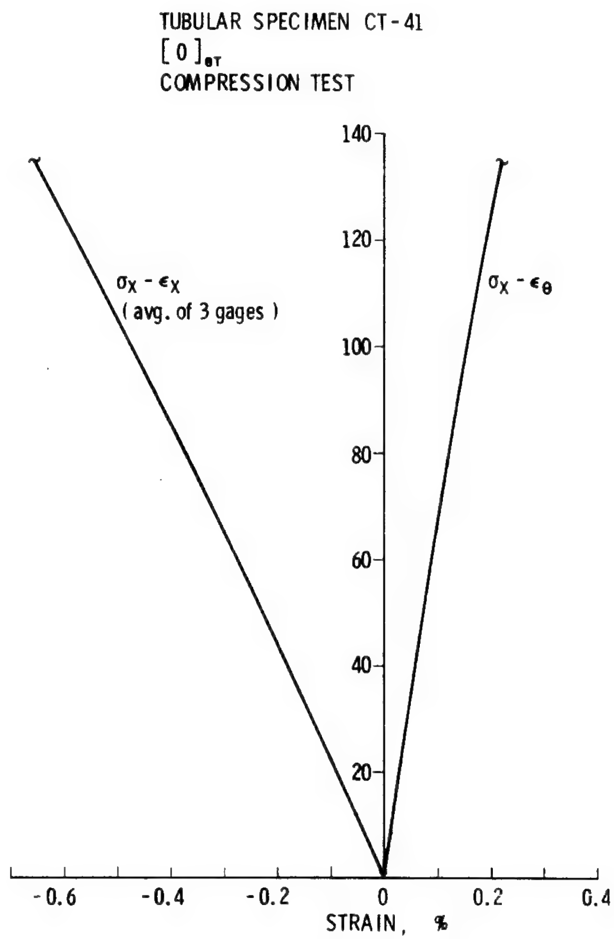


FIGURE III.32. STRESS-STRAIN CURVE, CT-41

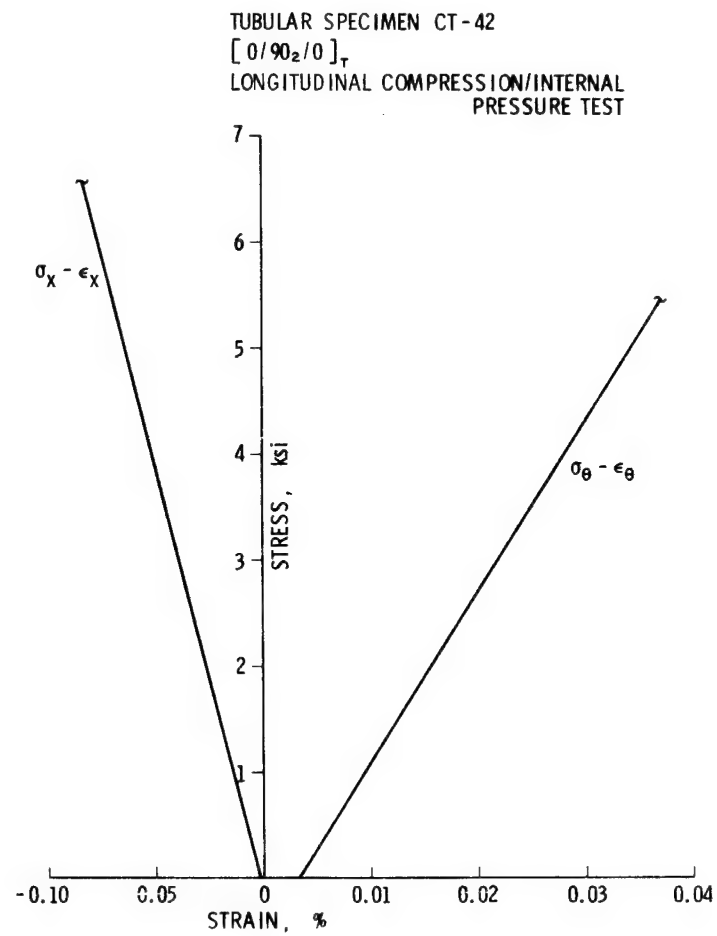


FIGURE III.33. STRESS-STRAIN CURVE, CT-42

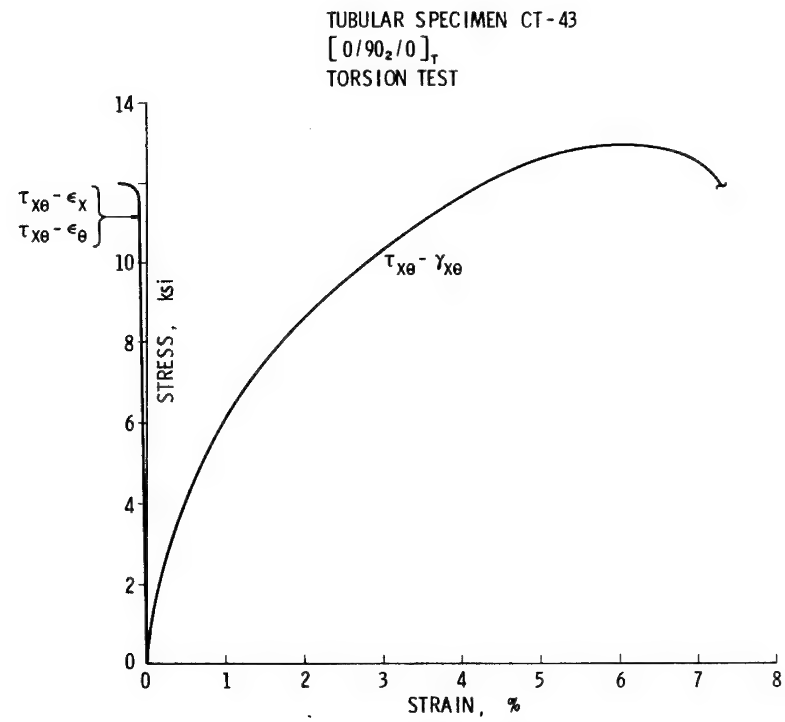


FIGURE III.34. STRESS-STRAIN CURVE, CT-43

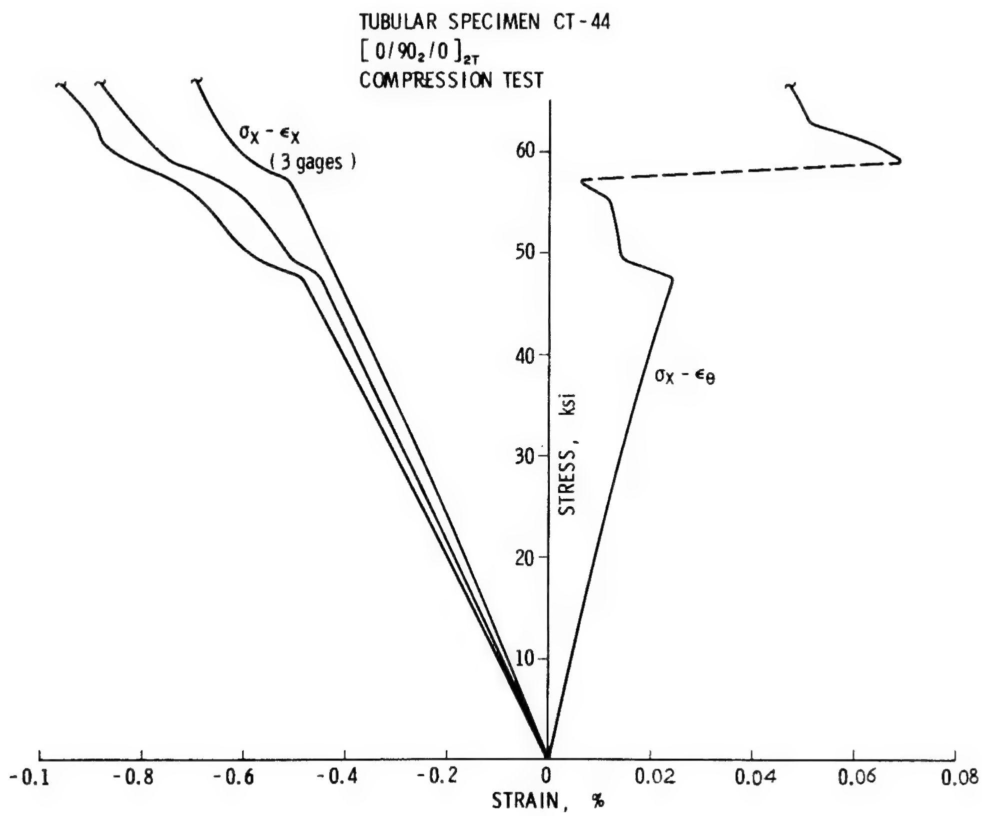


FIGURE III.35. STRESS-STRAIN CURVE, CT-44

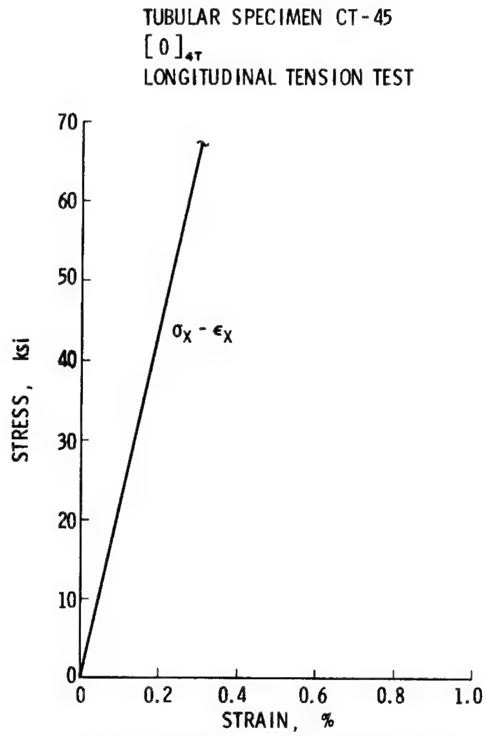


FIGURE III. 36. STRESS-STRAIN CURVE, CT-45

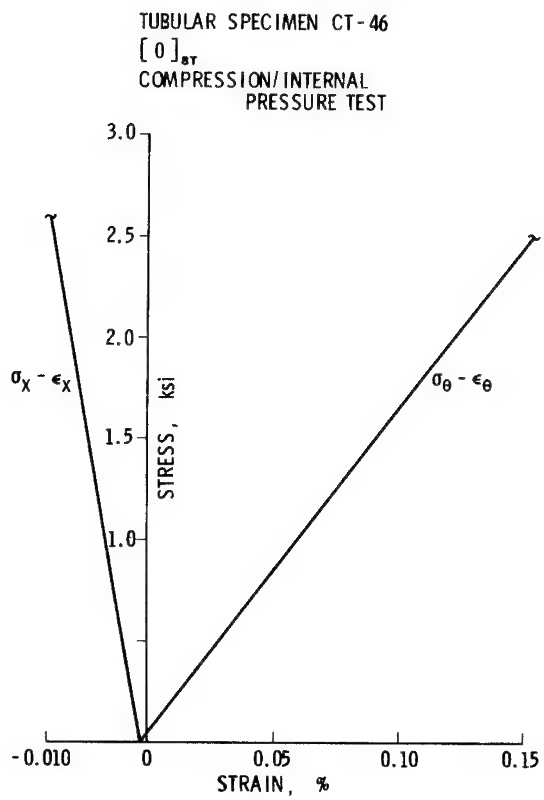


FIGURE III. 37. STRESS-STRAIN CURVE, CT-46

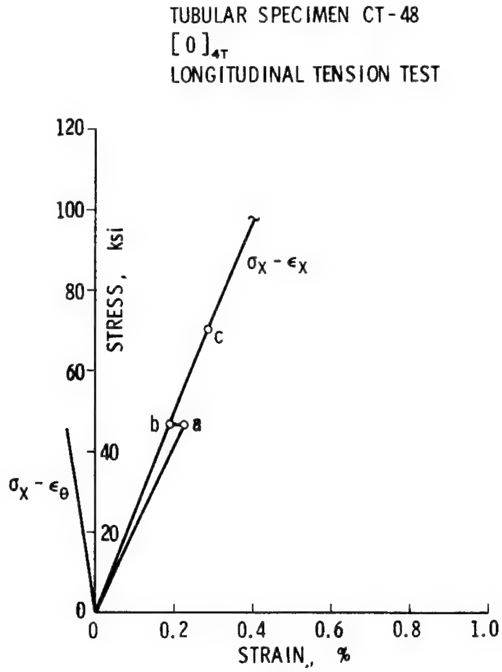


FIGURE III.38. STRESS-STRAIN CURVE, CT-48

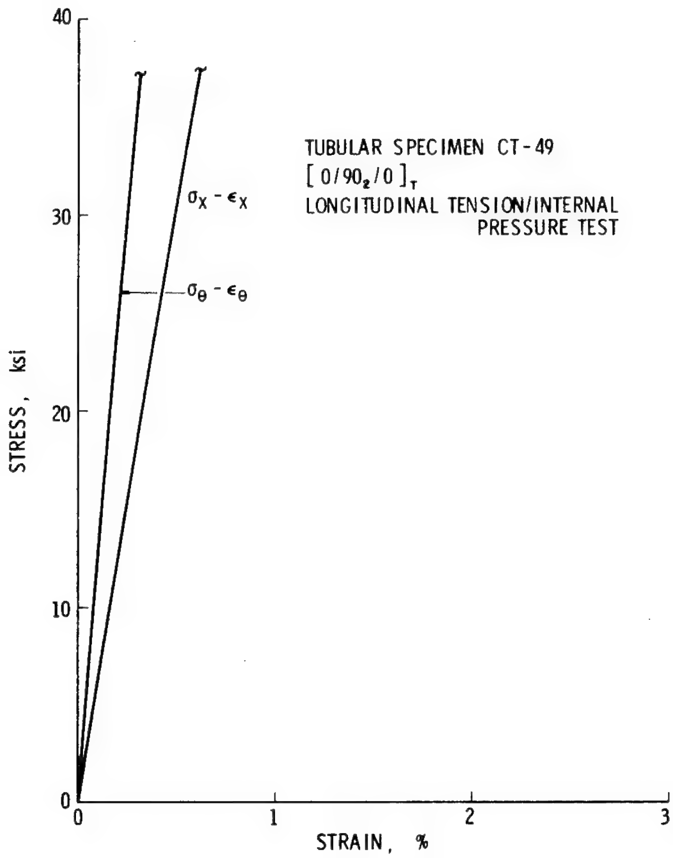


FIGURE III.39. STRESS-STRAIN CURVE, CT-49

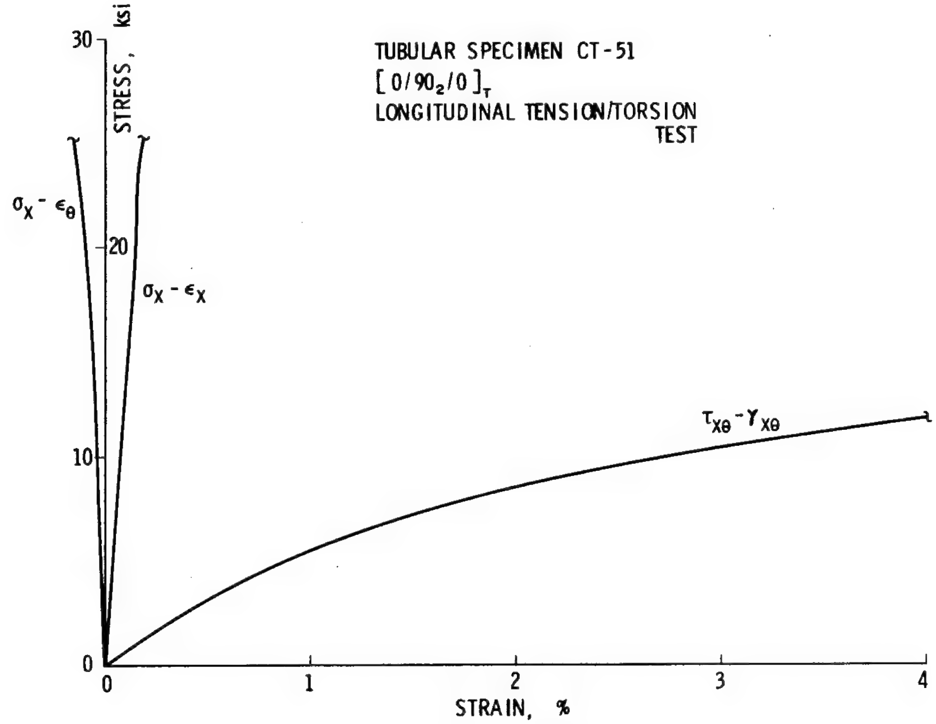


FIGURE III.40. STRESS-STRAIN CURVE, CT-51

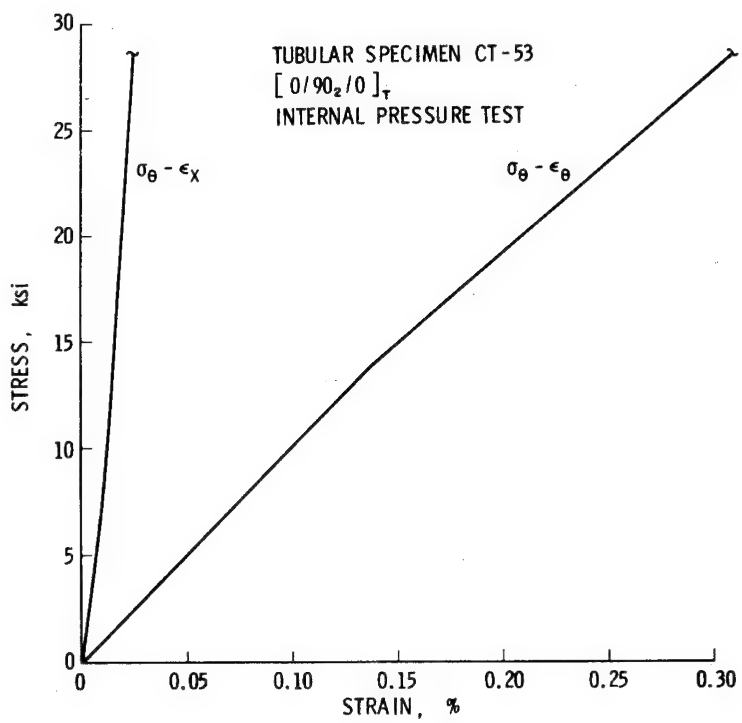


FIGURE III.41. STRESS-STRAIN CURVE, CT-53

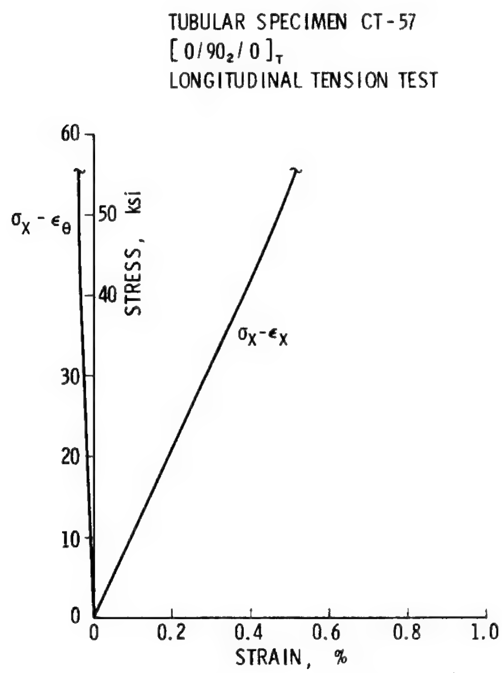


FIGURE III. 42. STRESS-STRAIN CURVE, CT-57

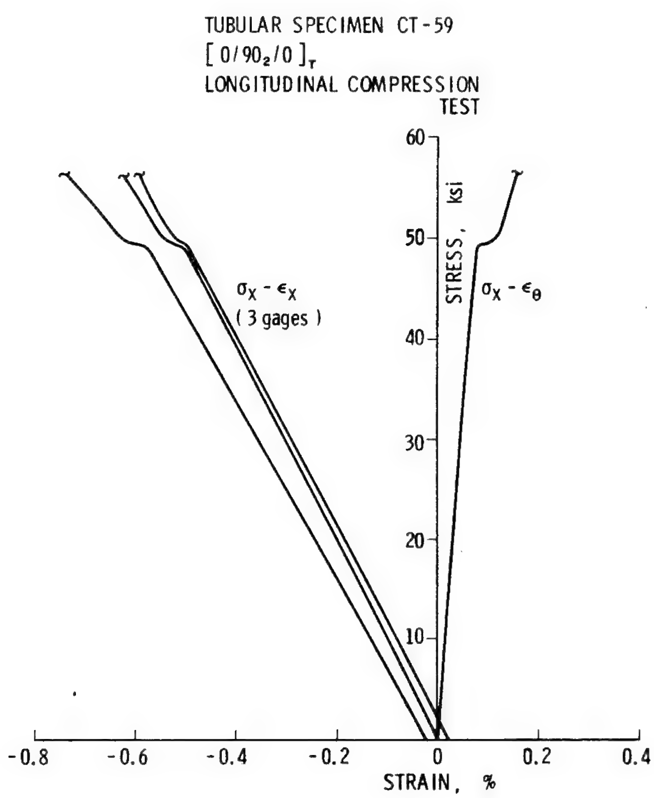
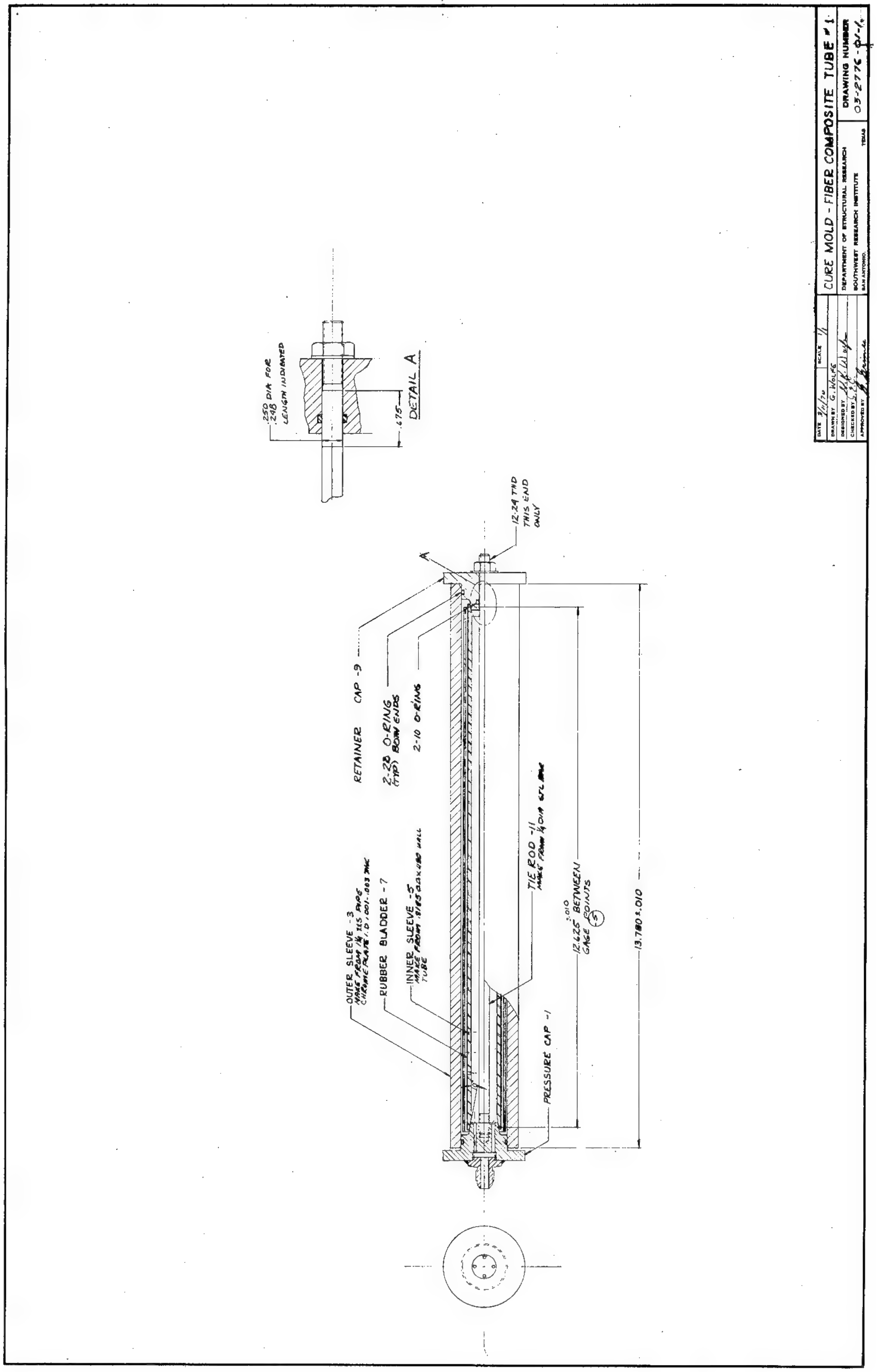


FIGURE III. 43. STRESS-STRAIN CURVE, CT-59

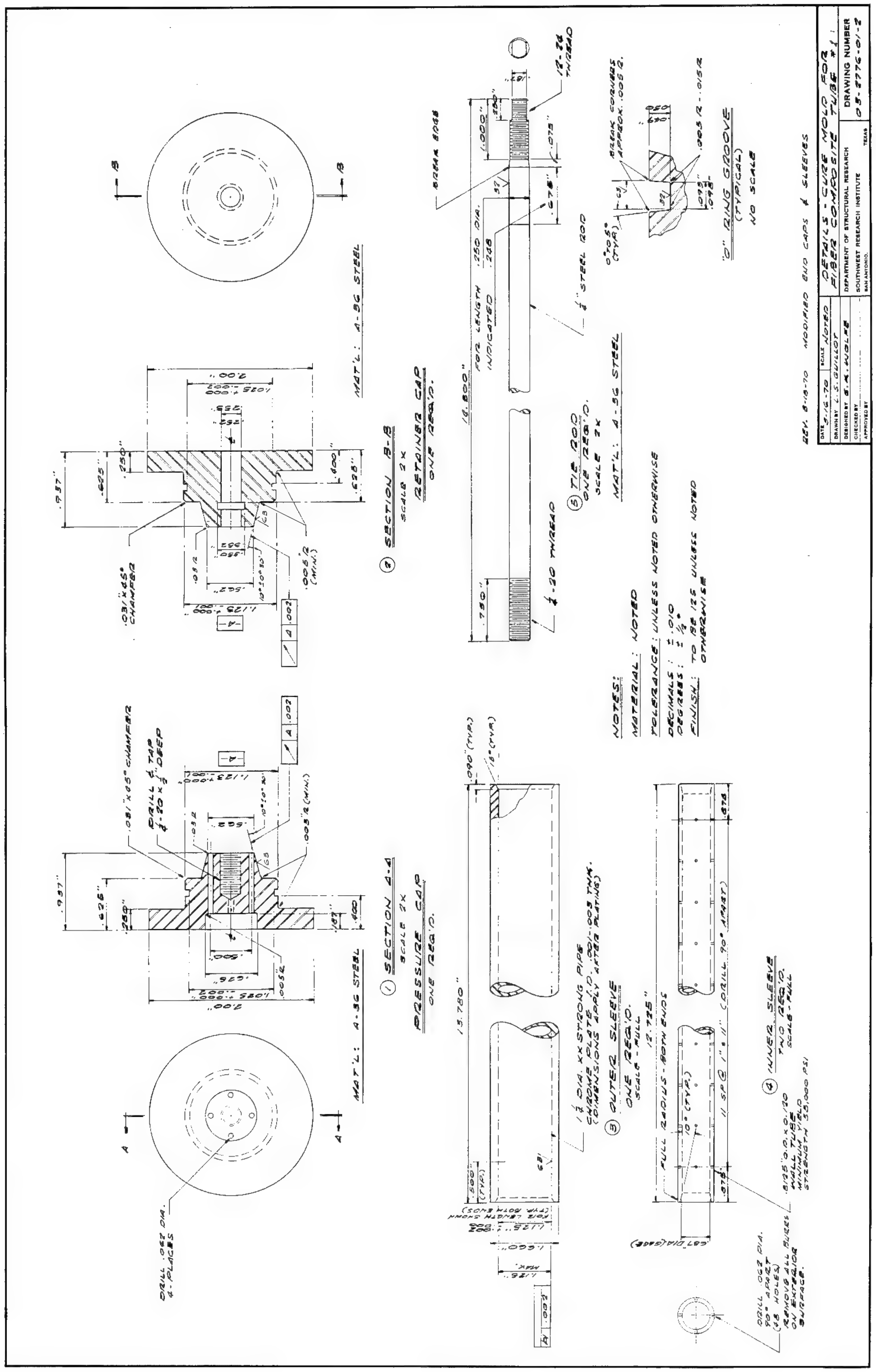
APPENDIX IV

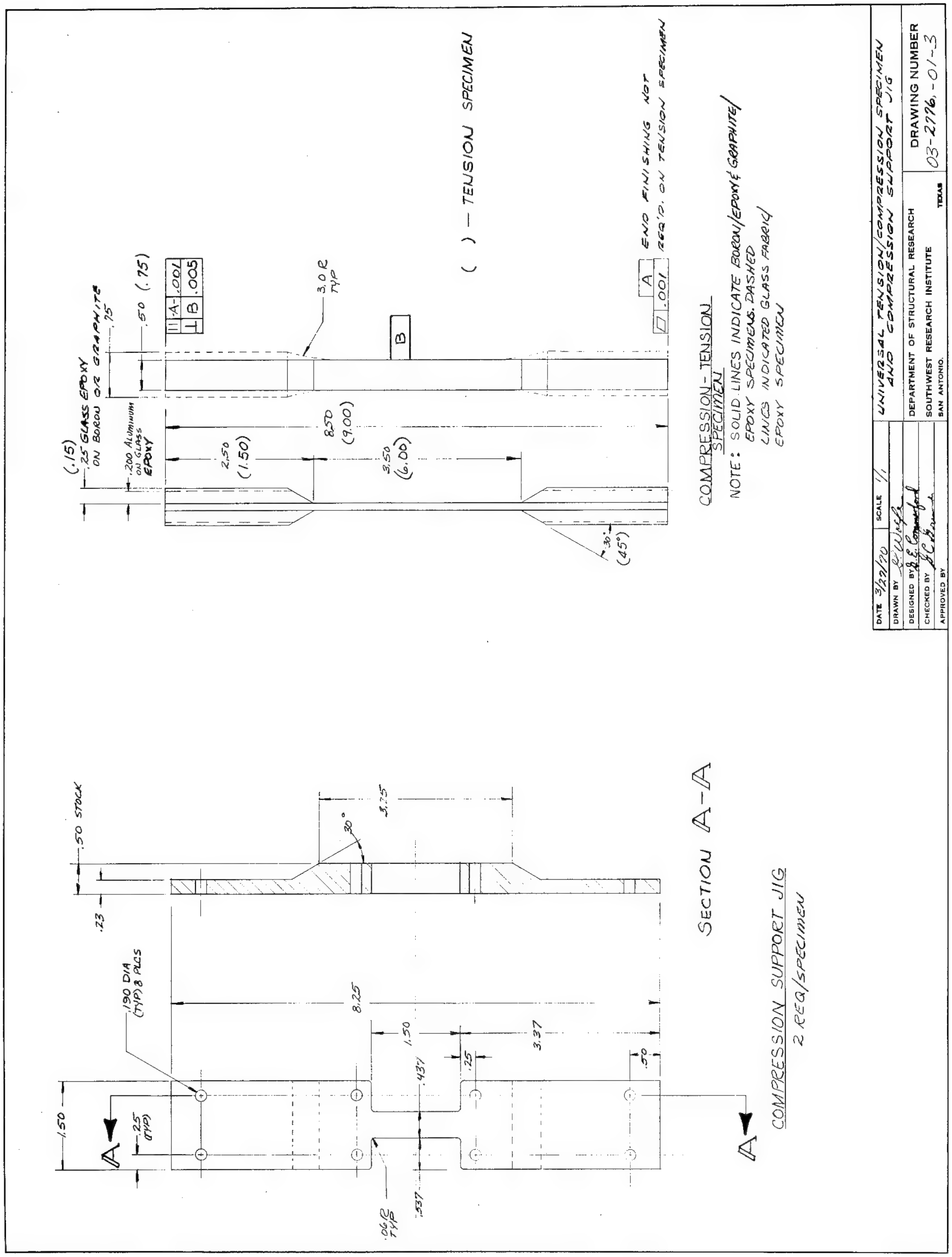
DRAWINGS

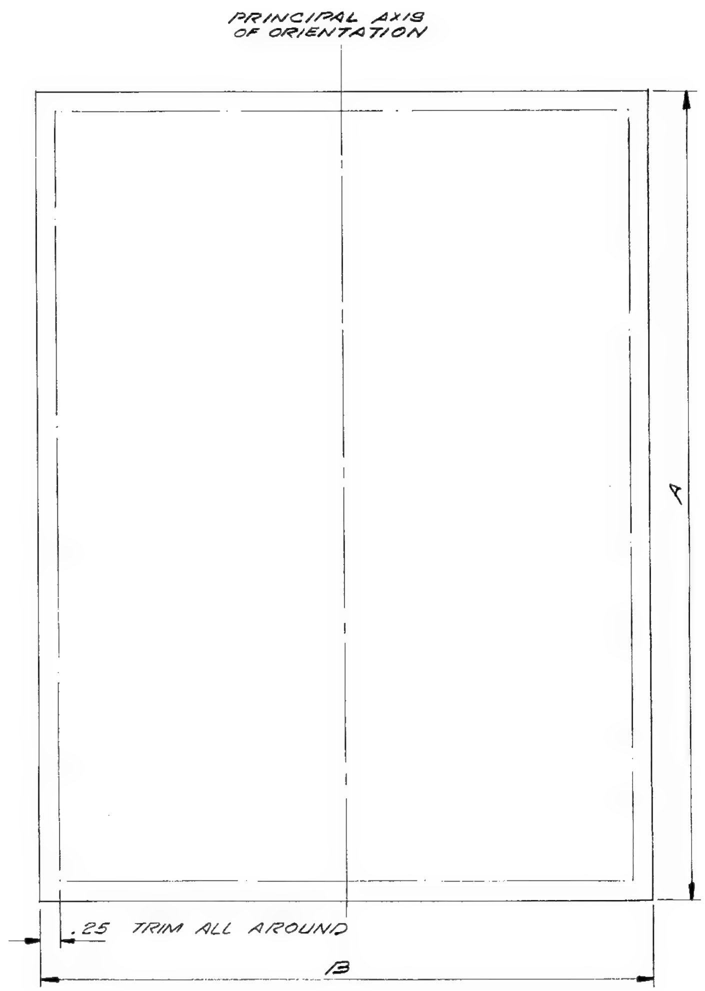
LIST OF DRAWINGS



CURE MOLD - FIBER COMPOSITE TUBE #1
DEPARTMENT OF STRUCTURAL RESEARCH
SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO
TEXAS
DRAWING NUMBER
DETAIL A
.250 DIA FOR .248 LENGTH INDICATED
.675
RETAINER CAP -9
2-28 O-RING (TYP) BOTH ENDS
2-10 O-RING
12-24 THD THIS END ONLY
OUTER SLEEVE -3
RUBBER BLADDER -7
INNER SLEEVE -5
TIE ROD -11
PRESSURE CAP -1
12.625 BETWEEN GAGE POINTS
13.780±.010


SECTION A-A
SCALE 2X
PRESSURE CAP
ONE REQ'D.
MAT'L: A-36 STEEL
DRILL .062 DIA. 4-PLACES
.031"X45° CHAMFER
DRILL & TAP 1/4-20 X 1/2" DEEP
SECTION B-B
SCALE 2X
RETAINER CAP
ONE REQ'D.
.031"X45° CHAMFER
OUTER SLEEVE
ONE REQ'D.
SCALE - FULL
1 1/4 DIA. XX STRONG PIPE
CHROME PLATE I.D. .001-.003 THK.
(DIMENSIONS APPLY AFTER PLATING)
INNER SLEEVE
TWO REQ'D.
SCALE - FULL
FULL RADIUS - BOTH ENDS
11 SP @ 1" = 11" (DRILL 90° APART)
DRILL .062 DIA. 90° APART (48 HOLES)
REMOVE ALL BURRS ON EXTERIOR SURFACE.
.8125" O.D. X 0.120 WALL TUBE
MINIMUM YIELD STRENGTH 55,000 PSI
TIE ROD
ONE REQ'D.
SCALE 2X
MAT'L: A-36 STEEL
1/4-20 THREAD
12-24 THREAD
1/4" STEEL ROD
BREAK EDGE
FOR LENGTH INDICATED
NOTES:
MATERIAL: NOTED
TOLERANCE: UNLESS NOTED OTHERWISE
DECIMALS: ±.010
DEGREES: ±1/2°
FINISH: TO BE 125 UNLESS NOTED OTHERWISE
"O" RING GROOVE
(TYPICAL)
NO SCALE
BREAK CORNERS APPROX. .005 R.
REV. 8-18-70 MODIFIED END CAPS & SLEEVES
DETAILS - CURE MOLD FOR FIBER COMPOSITE TUBE #1
DEPARTMENT OF STRUCTURAL RESEARCH
SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO, TEXAS
DRAWING NUMBER
03-2776-01-2
DRAWN BY L. S. GUILLOT
DESIGNED BY G. A. WOLFE

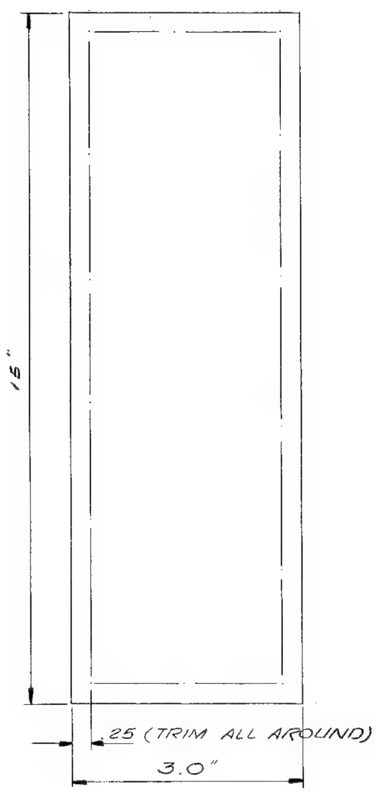

( ) — TENSION SPECIMEN
COMPRESSION - TENSION SPECIMEN
NOTE: SOLID LINES INDICATE BORON/EPOXY & GRAPHITE/EPOXY SPECIMENS. DASHED LINES INDICATED GLASS FABRIC/EPOXY SPECIMEN
END FINISHING NOT REQ'D. ON TENSION SPECIMEN
SECTION A-A
COMPRESSION SUPPORT JIG
2 REQ/SPECIMEN
UNIVERSAL TENSION/COMPRESSION SPECIMEN AND COMPRESSION SUPPORT JIG
DEPARTMENT OF STRUCTURAL RESEARCH
SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO, TEXAS
DRAWING NUMBER
03-2776-01-3
DATE 3/27/70
SCALE 1/1
DRAWN BY
DESIGNED BY
CHECKED BY
APPROVED BY



PART NO.	A (IN.)	B (IN.)
-3	10.5	8
-5	10.5	8
-7	8	10.5
-9	8	10.5
-11	10.5	15
-13	10.5	12

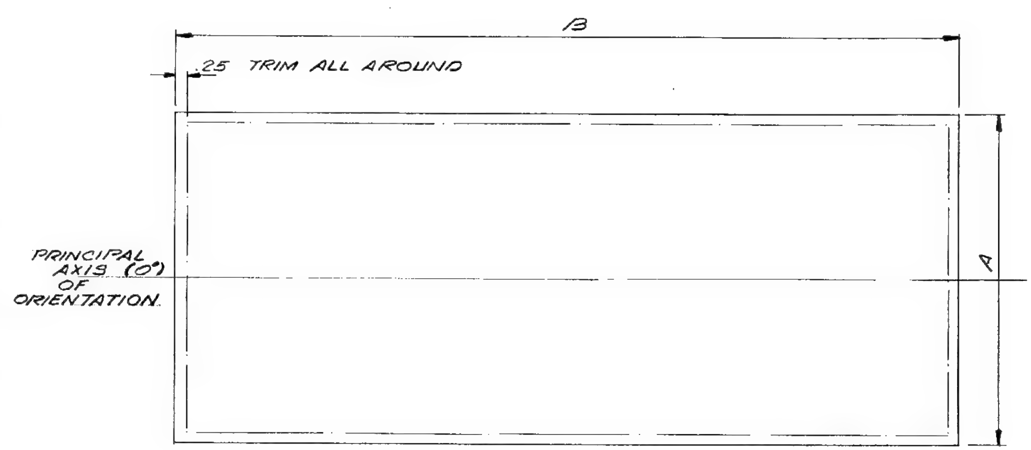
QTY. REQ'D.	PART OR IDENTIFYING NUMBER	NOMENCLATURE OR DESCRIPTION	SPECIFICATION	MATERIAL	ITEM
2	-13	PANEL $[0/90_2/0]_{3T}$	SwRI-S3-302	GRAPHITE EPOXY PRE-PREG HTS-TOW METER LENGTH	6
2	-11	PANEL $[0/90]_S$			5
1	-9	PANEL $[90]_{12T}$			4
2	-7	PANEL $[90]_{4T}$			3
1	-5	PANEL $[0]_{12T}$			2
1	-3	PANEL $[0]_{3T}$	SwRI-S3-302	GRAPHITE EPOXY PRE-PREG HTS-TOW METER LENGTH	1

DATE 4-2-70	SCALE FULL
DRAWN BY K.F. HOHN	PANEL DWG. - DAMAGE STRESS LEVELS - TASK II
DESIGNED BY [signature]	DEPARTMENT OF STRUCTURAL RESEARCH
CHECKED BY [signature] 4/7/70	SOUTHWEST RESEARCH INSTITUTE SAN ANTONIO, TEXAS
APPROVED BY [signature]	DRAWING NUMBER 03-2776-01-5



QTY. REQ'D	PART NO.	NOMENCLATURE DESCRIPTION	SPECIFICATION	MATERIAL	ITEM
1	-17	PANEL $[90/0]_{3S}$	SWRI-S3-302	GRAPHITE EPOXY PRE-PREG HTS-TOW METER LENGTH	8
1	-15	PANEL $[0/90]_{3S}$			7
1	-13	PANEL $[90]_{12T}$			6
1	-11	PANEL $[0]_{12T}$			5
1	-9	PANEL $[90/0]_{S}$			4
1	-7	PANEL $[0/90]_{S}$			3
1	-5	PANEL $[90]_{4T}$			2
1	-3	PANEL $[0]_{4T}$	SWRI-S3-302	GRAPHITE EPOXY PRE-PREG HTS-TOW METER LENGTH	1

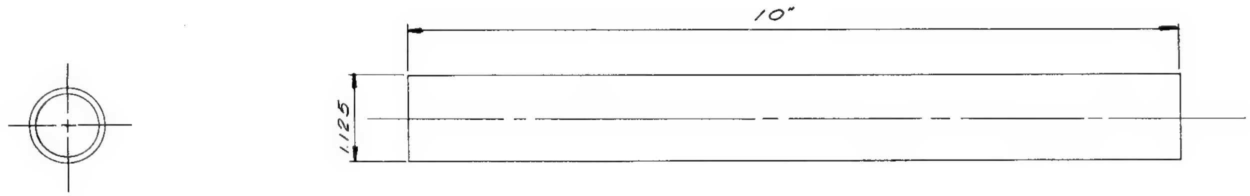
DATE 4-1-70 SCALE NONE	PANEL DWG. - DAMAGE STRESS LEVEL (Q.C.) TASK I
DRAWN BY K.F. HOHN	
DESIGNED BY [signature]	DEPARTMENT OF STRUCTURAL RESEARCH
CHECKED BY [signature] 4/7/70	SOUTHWEST RESEARCH INSTITUTE SAN ANTONIO, TEXAS
APPROVED BY [signature]	DRAWING NUMBER 03-2776-01-4



PART NO.	A (IN.)	B (IN.)
-3	8.5	20.5
-5	16	20.5
-7	9.5	20.5

QTY. REQ'D.	PART OR IDENTIFYING NUMBER	NOMENCLATURE OR DESCRIPTION	SPECIFICATION	MATERIAL	ITEM
0	-7	PANEL $[0/90_2/0]_{3T}$	SwRI-S3-302	GRAPHIC EPOXY PRE-PREG HTS.-TOW, METER LENGTH	3
2	-5	PANEL $[0/90_2/0]_{3T}$	↕	↕	2
1	-3	PANEL $[0/90_2/0]_{T}$	SwRI-S3-302	GRAPHIC EPOXY PRE-PREG HTS.-TOW, METER LENGTH	1

DATE 4-2-70 SCALE 1/2"-1"	PANEL DWG. - DAMAGE STRESS LEVELS - TASK III	
DRAWN BY K. F. HOHN		
DESIGNED BY G. E. Commerford	DEPARTMENT OF STRUCTURAL RESEARCH	DRAWING NUMBER
CHECKED BY G. K. Wolfe	SOUTHWEST RESEARCH INSTITUTE	03-2776-01-6
APPROVED BY Glenn C. Grimes	SAN ANTONIO, TEXAS	



NOTE:
FABRICATE TUBE PER SwRI-S3-102 & SwRI-S3-302

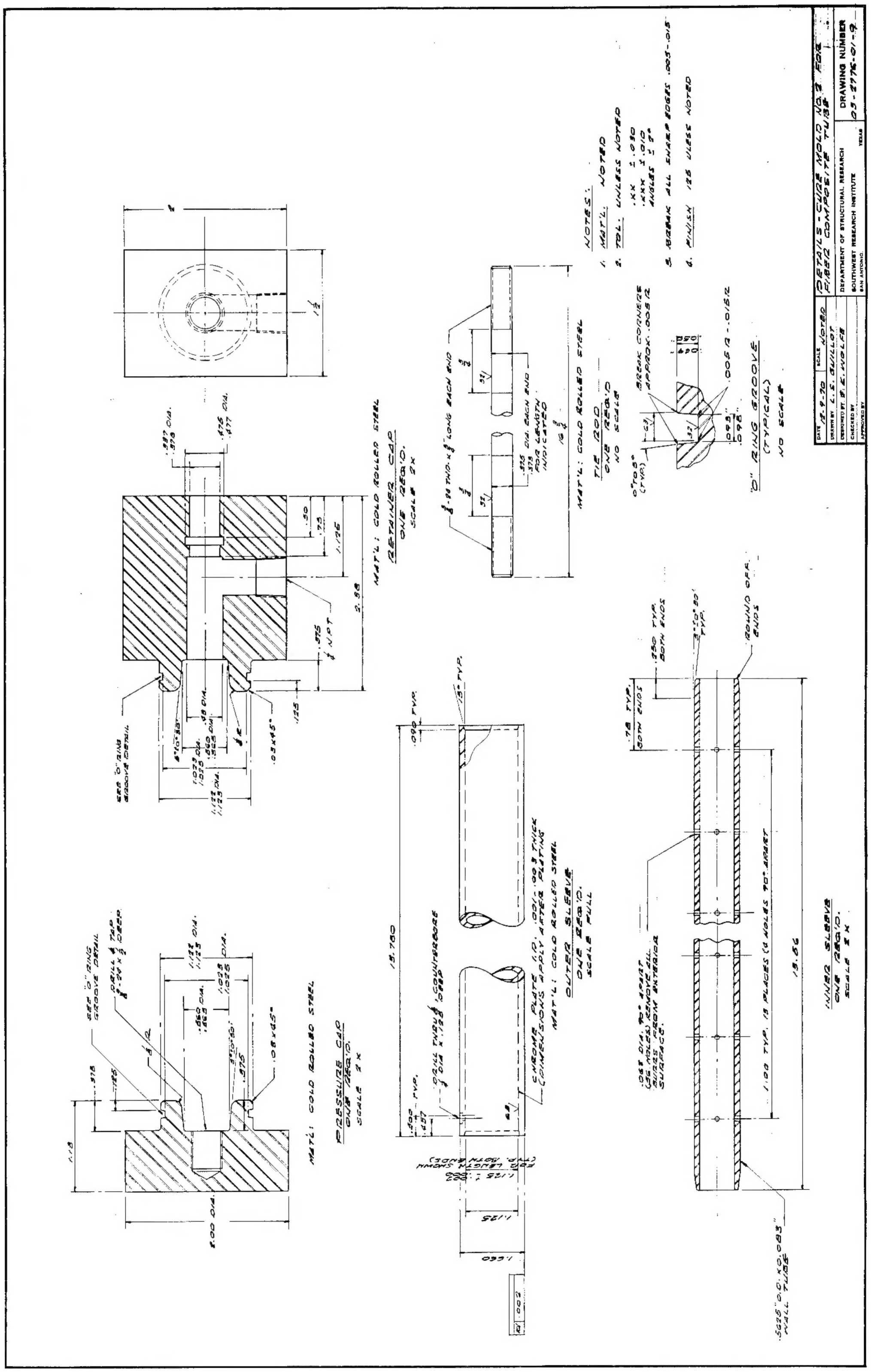
ORIENTATION	QTY	PART OR IDENTIFYING NO.	NOMENCLATURE DESCRIPTION	SPECIFICATION	MATERIAL	ITEM
$[0/90]_{4T}$	1	-13	TUBE 8 PLY	SwRI S3-302	GRAPHITE EPOXY PREPREG HTS -TOW METER LENGTH	6
$[0/90]_{3T}$	0	-11	6 PLY			5
$[0/90]_{2T}$	7	-9	4 PLY			4
$[90]_{4T}$	0	-7	4 PLY			3
$[0]_{4T}$	8	-5	4 PLY			2
$[0]_{8T}$	5	-3	TUBE 8 PLY	SwRI S3-302	GRAPHITE EPOXY PREPREG HTS-TOW METER LENGTH	1

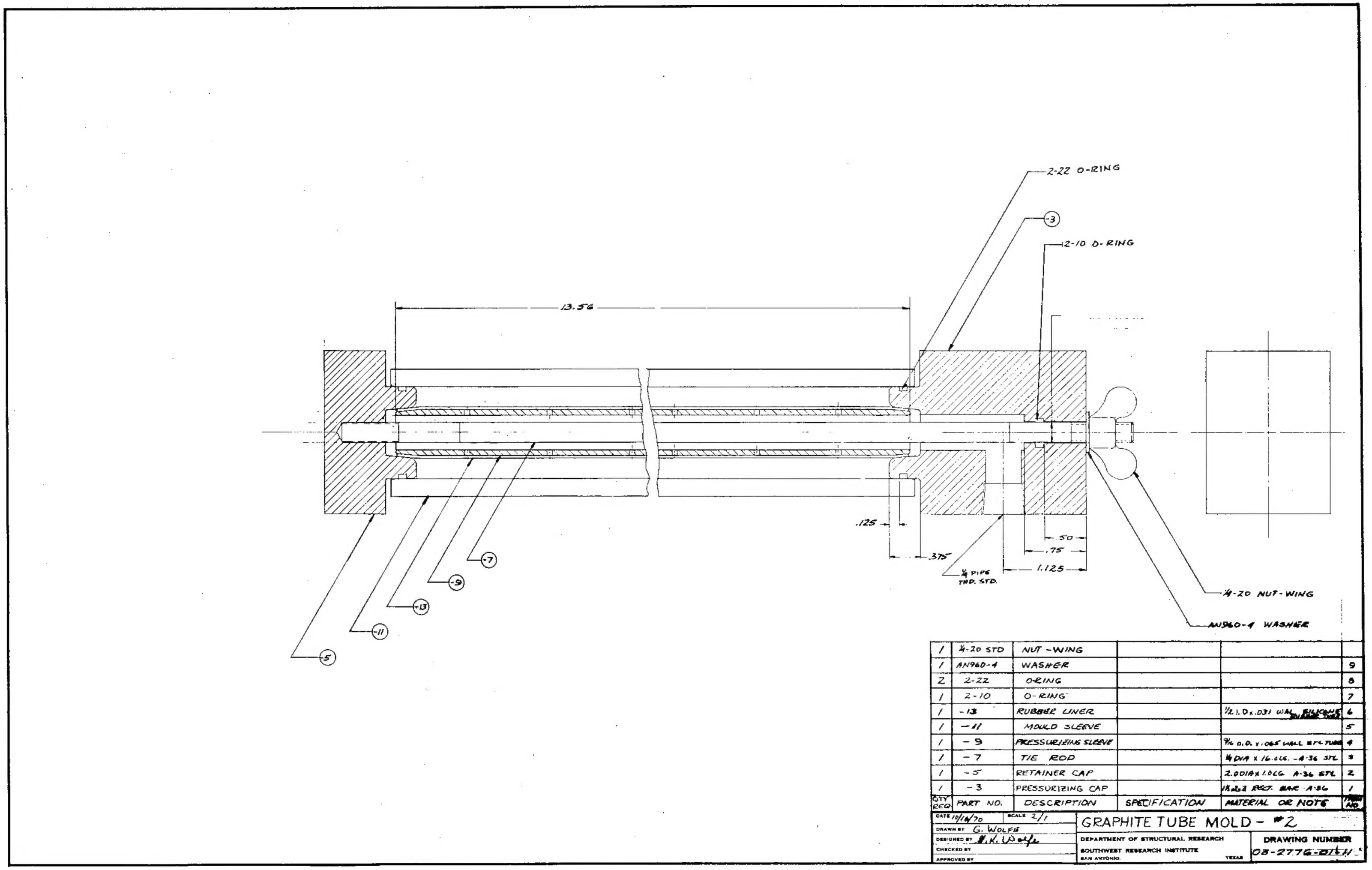
DATE 4-1-70 SCALE FULL
DRAWN BY M.F. HOHN
DESIGNED BY E.E. Commerford
CHECKED BY G.K. Wolf 4/7/70
APPROVED BY [signature]

TUBE DWG. - DAMAGE STRESS LEVELS

DEPARTMENT OF STRUCTURAL RESEARCH
SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO, TEXAS

DRAWING NUMBER
03-2776-01-7


DETAILS - CURE MOLD NO. 2 FOR FIBER COMPOSITE TUBE
DEPARTMENT OF STRUCTURAL RESEARCH
SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO TEXAS
DRAWING NUMBER
03-2776-01-9
DATE 12-9-70
SCALE NOTED
DRAWN BY L. S. GUILLOT
DESIGNED BY F. E. WOLFE
CHECKED BY
APPROVED BY
NOTES:
1. MAT'L: NOTED
2. TOL. UNLESS NOTED
.XX ±.030
.XXX ±.010
ANGLES ± 2°
3. BREAK ALL SHARP EDGES .005-.015
4. FINISH 125 UNLESS NOTED
PRESSURE CAP
ONE REQ'D.
SCALE 2X
RETAINER CAP
ONE REQ'D.
SCALE 2X
OUTER SLEEVE
ONE REQ'D.
SCALE FULL
TIE ROD
ONE REQ'D
NO SCALE
INNER SLEEVE
ONE REQ'D.
SCALE 2X
"O" RING GROOVE
(TYPICAL)
NO SCALE



2-22 O-RING
3
2-10 O-RING
13.56
.125
.375
¼ PIPE THD. STD.
.50
.75
1.125
¼-20 NUT-WING
AN960-4 WASHER
7
9
13
11
5
1 ¼-20 STD NUT-WING
1 AN960-4 WASHER 9
2 2-22 O-RING 8
1 2-10 O-RING 7
1 -13 RUBBER LINER 6
1 -11 MOULD SLEEVE 5
1 -9 PRESSURIZING SLEEVE 4
1 -7 TIE ROD 3
1 -5 RETAINER CAP 2.00 DIA x 1.0 LG. A-36 STL 2
1 -3 PRESSURIZING CAP 1
QTY REQ PART NO. DESCRIPTION SPECIFICATION MATERIAL OR NOTE
SCALE 2/1
DRAWN BY G. WOLFE
CHECKED BY
APPROVED BY
GRAPHITE TUBE MOLD - #2
DEPARTMENT OF STRUCTURAL RESEARCH
SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO TEXAS
DRAWING NUMBER

DOCUMENT CONTROL DATA - R & D

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Final Technical Report

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Glenn C. Grimes, George E. Commerford
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13. ABSTRACT

Significant damage stress levels in HTS/ERLA-2256 graphite epoxy composites were investigated in this research program. In order to do this it was necessary to establish high quality fabrication and inspection techniques for processing flat laminates and tubes and to experimentally characterize the mechanical and physical properties of the composite (lamina and laminate). Two significant damage stress levels were observed in $[0/90]_c$ laminates and related to the materials mechanical behavior. Empirically modified micro/macro-mechanics techniques and maximum strain theory were used to predict these stress levels as well as other composite properties with reasonable accuracy. These predicted values are used in normalizing the experimental data to one fiber and void volume for direct comparison and statistical analysis. Material design allowables and comfidence limits on the composite properties were established and possible application criteria proposed.

Significant milestones accomplished during the program include:

(1) the development of new processing techniques for the new prepreg version (Fiberite HY-E-1317B) of the HTS/ERLA-2256 graphite/epoxy material system, (2) development of quality seamless tube fabrication tooling and processing techniques, (3) establishment of improved instrumentation and automated data recording procedures along with semi-automated data reduction methods, (4) development of axial and biaxial tube testing techniques, and (5) the discovery of two significant micro-mechanical damage stress levels in the $[0/90]_c$ orientations which cause a change in subsequent loading behavior.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Composites						
Graphite/Epoxy						
Micromechanical Damage						
Significant Damage Stress (Strain) Levels						
Material Properties						
Design Allowables						
Tube Fabrication						
Tube Testing						
Laminating						